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MECHANICAL PROPERTIES OF MASS CONCRETE AT EARLY AGES

by

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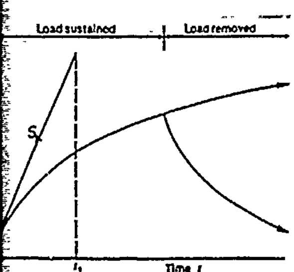

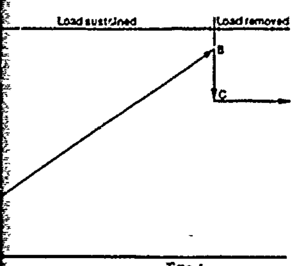

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13. ABSTRACT *(Maximum 200 words)*

A series of early-time material properties tests was conducted on mass concrete mixtures to be used in the construction of locks and dams along the Red River Waterway. Tests were conducted to determine creep, compressive strength, and Young's modulus of elasticity at ages of loading from 18 hr through several days. While a significant data base exists for the material properties of mass concrete at later ages, very few data exist for the early-time material properties of mass concrete. Therefore, this investigation provided a significant contribution to the existing data base. Two common simple models used to predict the strength and Young's modulus of elasticity as functions of time were selected for comparison with early-age mechanical properties test data. The data obtained from the early-time material properties tests were used to evaluate three viscoelastic creep models. The results of the investigation and the analysis are reported.

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PREFACE

The research described in this report was conducted for Headquarters, US Army Corps of Engineers (HQUSACE), under the Concrete Research Program, Work Unit 32260, Cracking of Concrete. Dr. Tony Liu, HQUSACE, was the Technical Monitor.

The research was performed at the US Army Engineer Waterways Experiment Station (WES) by members of the staff of the Structures Laboratory (SL), Concrete Technology Division (CTD), under the general supervision of Messrs. Bryant Mather, Chief, SL, J. T. Ballard, Assistant Chief, SL, and K. L. Saucier, Chief, CTD. Direction and technical guidance were provided by Mr. Michael I. Hammons, Applied Mechanics Group (AMG), CTD. This thesis was prepared by Mr. Donald Mark Smith, AMG, CTD.

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COL Larry B. Fulton, EN, was Commander and Director of WES during this investigation and preparation of this report. Dr. Robert W. Whalin was Technical Director of WES.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
inches	25.4	millimetres
kips (force)	4.448222	kilonewtons
pound (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C=(5/9) (F-32). To obtain kelvin (K) readings, use: K=(5/9) (F-32) + 273.15.

MECHANICAL PROPERTIES OF MASS CONCRETE AT EARLY AGES

CHAPTER I: INTRODUCTION

Background

1. Two of the three large dams completed by the Corps of Engineers in the last 20 years have developed cracking which has required costly repairs and, in one case, caused serious leakage. The dams involved, Dworshak in Idaho, and Richard B. Russell on the Georgia-South Carolina border, have cracked in a similar mode. In those monoliths where cracking has occurred, a vertical crack forms in the upstream face midway between the monolith joints and, with time, tends to propagate downstream normal to the axis of the dam. In May 1980, when the reservoir at Russell Dam reached its full pool elevation, a crack in one of the monoliths opened approximately 2.5 mm allowing flows of up to 29 m^3 per minute into the galleries. In addition to this type of cracking, the Corps has had repeated problems of cracking in concrete overlays and other structural elements of any significant size [1].

2. A three-dimensional finite-element model for concrete which includes material aging, creep, shrinkage, and thermal effects has recently been developed for the Corps by Anatech International Corporation working under contract for the Waterways Experiment Station. Through the use of this model in a proven general-purpose finite-element code it has been possible for engineers to determine the concrete mixture proportions and construction procedures which will yield the most cost-effective, safe, and serviceable structure for a given application [2].

3. Recent analytical and experimental studies performed in the Concrete Technology Division (CTD) have generated considerable interest in the thermal stresses and related phenomena which occur at very early ages of concrete placed in mass structures. These studies have shown that an accurate determination of concrete material properties at early ages (especially time of setting through 3 days) is essential in performing an accurate analytical prediction of thermal stresses and related cracking in a mass concrete structure. A series of early-time material properties tests was performed on mass

concrete mixtures to be used in the construction of locks and dams. The results of this investigation and an analysis are reported herein.

Literature Review

4. The ancient Egyptians, Greeks, and Romans were among the first people to use concrete as a building material. The cracking associated with concrete has been a major problem since that time [3]. As mentioned earlier, the cracking of mass concrete structures has generated a great deal of interest and concern within the US Army Corps of Engineers.

5. Given the experiences with Dworshak and Russell Dams, an important question must be raised of why significant cracking occurred in two structures designed with verified computer programs using well-established procedures. It should also be noted that this cracking occurred, in some instances, before any water was impounded behind the dam. This observation rules out hydrostatic loading as the cause of the cracks, and lends credibility to the idea that the cracks were due to excessive thermal strains. These considerations led to a conclusion that the theoretical and computational methods used in the analysis and design of mass concrete structures should be modified or developed to deal with cracking problems. Material properties test methods should also be developed to provide data consistent with the requirements set forth by the computational procedures [1].

6. The majority of research in the area of concrete cracking has been and is concerned with materials that have attained a steady-state condition with regard to material properties as a function of time and temperature [1]. This steady state condition occurs in most concretes at later ages. Due to this fact, there are very few data available on concrete material properties during the time that concrete is undergoing the greatest amount of thermal activity and physical change (i.e. early ages, less than 3 days) [2].

7. Mass concrete structures are constructed incrementally in layers commonly called lifts. Lift heights and sequencing are controlled by thermal stress considerations, concrete batch plant capacity, and structural geometry. Careful consideration given to preventing construction-related cracking in the specification-writing phase of a construction project leads to a more durable, cost-effective structure. Incremental-construction analyses have shown that

the cost of materials, heat generation and associated thermal stresses, and cost of construction can be reduced through the use of higher proportions of fly ash in the concrete mixtures [4].

8. The rate of gain of compressive strength and elastic modulus, especially in the first few days after placement, are critical parameters in predicting construction-related cracking in mass concrete structures. In addition, the removal and anchorage of formwork depend upon the early-time strength gain characteristics of the concrete mixture [5].

9. It should be noted that in a thermal-stress analysis of a mass concrete structure the creep, shrinkage, and thermal strains are of the same order of magnitude as the elastic strains. Therefore, the accurate characterization, modeling, and prediction of these material properties are of the greatest importance in the analysis of a mass concrete structure [3].

Objective

10. The objective of this investigation was to determine the characteristics of compressive strength, Young's modulus of elasticity, and creep at very early ages in concrete. The impact of these parameters on the constitutive models used in the solution of incremental-construction thermal stress analysis problems will be evaluated. While a significant data base exists for the material properties of mass concrete at later times or ages, very few data exist for the early-time material properties of mass concrete. Therefore, this investigation makes a significant contribution to the existing data base.

Scope

11. Due to the significant changes occurring in concrete at ages under 48 hours, tests were conducted to determine creep response, compressive strength, and elastic modulus for ages of loading from 18 hours through several days. Techniques and equipment for performing these tests were adapted to measure the low loads and large deformations observed in concrete loaded at very early ages. The characteristics of creep, strength gain, and modulus gain at very early ages must be clearly understood in order to accurately

predict thermal stresses and related cracking in mass concrete structures. Tests conducted at WES have shown that the measurement of creep in concrete at very early ages is a difficult and complex task, because the specimen creeps during the time required for application of the load. This makes the separation of the elastic strain from the creep strain quite difficult.

12. The data obtained from the early-time material properties tests will be used to evaluate three viscoelastic models. These models are the American Concrete Institute (ACI) creep equation, the WES Time-Dependent Material Properties Model (UMAT) creep equation, and the Bazant Sinh-Double Power Law (SDPL) creep formulation.

CHAPTER II: CONCRETE MATERIAL PROPERTIES

General

13. To properly address the properties of mass concrete at early ages, it is necessary to understand the general physical, thermal, and mechanical properties of concrete at all ages. An extensive database currently exists which addresses these issues. A number of rational and consistent constitutive models currently exist which can accurately predict the response of concrete subjected to various loading conditions. This chapter will present an overview of the properties of concrete.

Physical and Thermal Properties

14. The physical and thermal properties of concrete are highly dependent on the types and relative proportions of the materials used in producing a given concrete mixture. These properties undergo significant changes during the first 48 to 72 hours after concrete is placed. General characteristics of the physical and thermal properties relevant to this investigation are briefly described below.

- a. Density or Unit Weight. The density of mass concrete is approximately the same as that of conventional concrete. The density of concrete is a relatively stable property and does not undergo significant changes at early times. The density of concrete is primarily used in calculating loads from construction and service environments.

- b. Porosity. The porosity of concrete is a critical property that must be accounted for in order to understand moisture migration during and after concrete hardening. Many of the theories concerning the mechanism of creep in concrete address the matter as a function of moisture migration as a result of loading.

- c. Moisture Content. As stated above, moisture migration is believed to be one of the mechanisms which cause concrete to deform under sustained loads, i.e. to creep.

- d. Adiabatic Temperature Rise. Deep within the interior of a mass concrete structure an adiabatic condition is approached. During the hydration of cement a great deal of heat can be generated. The models used in predicting temperature distributions within mass concrete structures use the adiabatic temperature rise as the driving function for making predictions.

e. Thermal Coefficient of Expansion, Thermal Conductivity, Thermal Diffusivity, and Specific Heat. These properties have a significant indirect effect on concrete volume change.

Mechanical Properties

15. The mechanical properties of concrete at very early ages vary significantly from the properties of mature concrete. The concrete properties such as stress-strain behavior, unconfined uniaxial compressive strength, modulus of elasticity, tensile strength, creep and stress relaxation, shrinkage, contraction and expansion expressed as functions of time, are used in the analysis and design of mass concrete structures. A brief description of these properties is presented below:

a. Stress-strain Behavior in Uniaxial Compression. The shape of the stress-strain curve for concrete changes dramatically within the first few days after concrete is placed. During early times the ascending portion of the curve is less linear and much flatter than for mature concrete. A great deal of this can be contributed to creep and other forms of non-linear behavior during loading.

b. Unconfined Compressive Strength. Many factors influence the strength of concrete. Some of the main factors include: water-cement ratio, degree of compaction, temperature, and age. In this thesis the influence of age on strength will be one of the main points of emphasis, with early times being the period of primary interest.

c. Modulus of Elasticity. The values of the Young's modulus of elasticity for concrete at early ages are vastly different from that of mature concrete. It is also important to note that the modulus of elasticity for concrete at early ages is increasing at a substantial rate.

d. Tensile Strength. The tensile strength of concrete varies with age just as the compressive strength varies with age. The tensile strength of concrete is normally estimated to be 10 % of the compressive strength at the same age. Further investigation into this area is needed, but was outside the scope of this research effort.

e. Creep. The time-dependent deformation of hardened concrete subjected to a sustained load is defined as creep. This increase is obtained by subtracting from the strain in a loaded specimen the sum of the elastic strain due to applied stress, the shrinkage and thermal strain in an identical load free specimen. Creep is particularly related to strength, elastic modulus, and age at loading. The primary effect of this phenomena is, in general, the relief of stress due to shrinkage, contraction, or expansion. This property of concrete varies greatly with age and is associated with moisture migration and other viscoelastic behavior.

f. Shrinkage. The time-dependent decrease of concrete volume due to loss of moisture is shrinkage. These changes in volume occur without stress attributable to actions external to the concrete. A detailed study of these phenomena was outside the scope of this investigation.

g. Contraction and Expansion. Contraction or expansion is the algebraic sum of concrete volume changes occurring as the result of thermal variations caused by heat of hydration of cement or by changes in the ambient temperature. A detailed study of these phenomena was also outside the scope of this investigation.

CHAPTER III: CONCRETE MODELS

General

16. Constitutive models are used to relate states of stress to associated states of strain. This is a very general definition of the term "constitutive model". For the purposes of this report only constitutive models capable of predicting time-dependent behavior will be discussed. Time-insensitive models based on elasticity and plasticity will not be discussed. Two common simple models used to predict the relationship between strength and elastic modulus as it changes with time, along with more sophisticated models for predicting creep, will be discussed in this section.

Strength and Modulus Equations

17. Compressive strength and elastic modulus are roughly linear over the period from time of final setting to 14 days when plotted against the logarithm of time. Therefore, equations of the form

$$f_c(t) = a_0 + a_1 \log(t)$$

and

$$E(t) = b_0 + b_1 \log(t)$$

will be used to predict Young's elastic modulus (E) and compressive strength (f_c) as functions of time, where a_0, a_1, b_0 and b_1 are constants determined in a least-squares curve fit of test data.

18. The static modulus of elasticity (secant modulus) is the linearized instantaneous (1 to 5 minutes) stress-strain relationship. It is a time-dependent concrete material property. The ACI Building Code 318-90 gives the following equation for the static modulus of elasticity (in psi) of concrete:

$$E_{ct} = 57000\sqrt{(f'_c)_t}$$

where $(f'_c)_t$ is the compressive strength in psi at time t [6].

Theory and Prediction of Creep

19. A number of theories about creep have been proposed over the years but no single theory is capable of accounting for all the observed phenomena. An understanding of the mechanism of creep is important in understanding the theories that have been applied to predicting creep response of concrete. According to ACI Committee 209, the main mechanisms which describe creep are:

a. Viscous flow of the cement paste caused by sliding or shear of the gel particles lubricated by layers of adsorbed water.

b. Consolidation due to seepage in the form of adsorbed water or the decomposition of interlayer hydrate water.

c. Delayed elasticity due to the cement paste acting as a restraint on the elastic deformation of the skeleton formed by the aggregate and gel particles.

d. Permanent deformation caused by local fracture (microcracking and failure) as well as recrystallization and formation of new physical bonds [7].

20. A satisfactory theory of creep must explain in a consistent manner the behavior of concrete under various environmental conditions and various states of stress. With this in mind, any theory for predicting the creep characteristics of concrete at all ages must be based on theoretical and experimental backgrounds. The following discussion of some current creep models will begin with simple rheological models and progress toward more complicated viscoelastic models.

Rheological Models

21. The study of the flow properties of a material, hence the relationships between stresses and strains in a very general sense is rheology. Theoretical ideal bodies with strictly defined properties are proposed and combined to result in a behavior similar to that of real materials. The most common ideal bodies used to build up a rheological model are an elastic spring and a dashpot. The spring is used to represent elastic behavior and the dashpot is used to represent viscous (time-dependent flow behavior). These basic elements can be combined and built into rheological models of varying

complexity. The two basic models used are the Kelvin model and the Maxwell model, shown in Figure 1. In the Kelvin model the spring and the dashpot are in parallel so that they undergo the same displacement. This results in the total force on the Kelvin model being the sum of the forces on the individual elements. In the Maxwell model the spring and the dashpot are in series so that they take the same load. This results in the total displacement of a Maxwell model being the sum of the displacements of the two elements.

Kelvin Model

22. Consider the Kelvin model, when a load is applied suddenly, the element exhibits no initial deformation. However, the deformation increases with time exponentially. Initially, all the load is carried by the dashpot but is transferred to the spring at a decreasing rate so that at infinite time the spring would carry the entire load. Because of this, a Kelvin model approaches an asymptotic value equal to the instantaneous deformation of the spring alone, $P\alpha$. The equation of a Kelvin model is given as:

$$P=\frac{1}{\alpha}x + v\frac{\partial x}{dt}$$

where P is the applied force, α is the spring compliance, x is the deformation of the model, v is the viscosity of the dashpot, and t is time. The solution of the Kelvin model equation is of the form:

$$x=P\alpha\,(1-e^{-\frac{t}{t_1}})$$

where $t_1=(\alpha v)$ is equal to the time in which the ultimate deformation would be reached at a constant rate of deformation equal to the initial value. The deformational response of a Kelvin model is shown in Figure 2. A Kelvin model is well-suited for problems involving delayed elasticity and strain recovery with some permanent deformation.

Maxwell Model

23. The characteristics of a Maxwell model are somewhat different from a Kelvin model. In a Maxwell model, when a load is applied, the extension of the spring is:

$$x_s = \alpha P$$

where α is the spring compliance. The deformation of the dashpot is given as:

$$\frac{dx_d}{dt} = \frac{P}{v}$$

where v is the viscosity of the liquid in the dashpot.

24. The total viscosity of the model is:

$$x = x_s + x_d$$

Since the load carried by the two elements in series is the same,

$$P = \frac{x_s}{\alpha} = v\frac{dx_d}{dt}$$

Therefore the differential equation of the Maxwell model is given as:

$$\frac{dP}{dt}\alpha + \frac{P}{v} = \frac{dx}{dt}$$

25. Figure 2 shows the deformational behavior of a Maxwell model under a sustained load and after its removal the existence of a permanent deformation. It should also be noted that, when subjected to a constant deformation, a Maxwell model exhibits the property of stress relaxation. Since dx/dt = 0 the solution to the differential equation yields that

$$P = P_o \, e^{-\frac{t}{\alpha v}}$$

where P_o is the initial load. From this, it can be seen that the relaxation is exponential and complete after an infinite time. The Maxwell model is very useful in relaxation problems.

26. Rheological models imply nothing about the physical mechanisms responsible for the observed behavior of concrete but give an overall description of the phenomena of deformation. The solution forms for the rheological models are the basic forms for most creep models, and they provide an excellent background for further understanding of the more complicated viscoelastic models such as the Bazant creep formulation, the ACI creep formulation, and the WES-UMAT time-dependent material properties model. These models will be addressed in the next section.

Viscoelastic Creep Models

27. In the following methods the specific creep, $C(t, t_0)$, is defined as the ratio of creep strain at any age t, after application of stress at age t_o, to the applied stress. This is shown in the following equation:

$$C(t, t_o) = \frac{\epsilon_{creep}}{\sigma_{applied}}$$

Bazant Sinh-Double Power Law

28. A simple basic creep formula for concrete based on Sinh-Double Power Law (SDPL) has been proposed by Bazant, et al [10]. The formula is designed to predict only load induced creep and not drying creep or shrinkage. As presented, the formula allowed a good fit of experimental data from the literature. However, early time response was not thoroughly investigated. The formula is presented below and will be evaluated against early-age test data in Chapter 5. The SDPL creep compliance (specific creep) function $C(t,t_o)$ represents the strain per unit stress at any age t caused by a uniaxial stress applied on concrete at age t_o.

$$C(t, t_0) = \frac{\psi_0}{E_0} \sinh^{-1}\xi$$

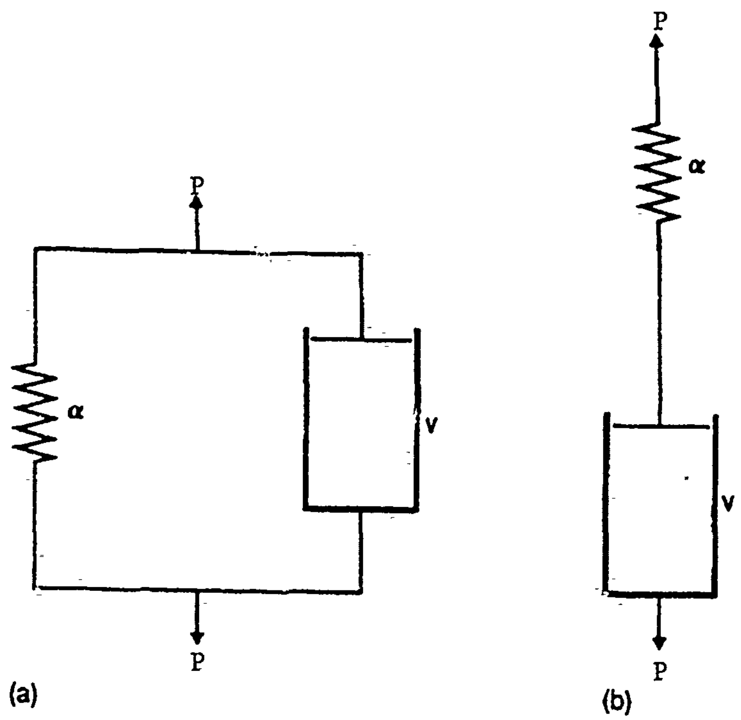

Figure 1. (a) Kelvin Model, (b) Maxwell Model

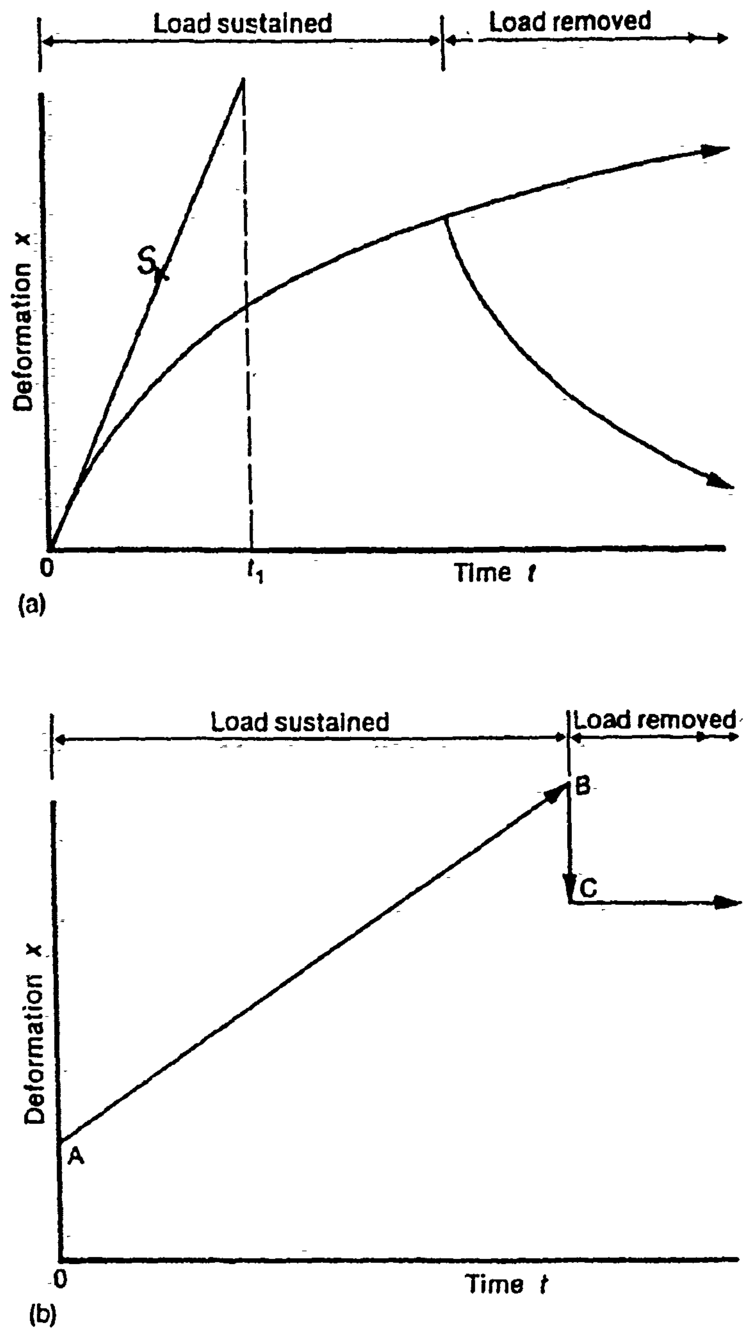

Figure 2. (a) Deformational Response of a Kelvin Model,
(b) Deformational Response of a Maxwell Model

where:

$$\xi=\psi_1(t_0^{-m}+\alpha)(t-t_0)^n$$

E_o represents the elastic modulus at the time of loading and ψ_o, ψ_1, α, n, and m are five constants determined from fits of $C(t,t_o)$ to calibration creep test data.

ACI creep formula

29. Based largely on experimental work on concretes at ages greater than 7 days, ACI Committee 209 [7] recommends the following general equation for predicting creep of concrete at any time:

$$C(t,t_0)=\frac{(t-t_0)^{\psi}}{10+(t-t_0)^{\psi}}C_{\infty}(t_0)$$

where $C(t,t_o)$ represents the strain per unit stress at any age t caused by a uniaxial stress applied on concrete at age t_o and $C_\infty(t_o)$ is known as the ultimate specific creep. A more specific form of the ACI equation allows for the exponent, ψ, to be set equal to 0.6 and is the most widely used form of the equation. ACI gives the following procedure for estimating $C_\infty(t_o)$ from specimen size, curing conditions, and mixture properties:

$$C_{\infty}(t_o)=2.35x_1x_2x_3x_4x_5x_6$$

where x_1, $x_2 \ldots x_6$ are constants calculated from the concrete mixture proportions and material properties. This type of procedure is only necessary when test data are not available. For the purposes of this report the specific creep values at the end of the creep tests will be used to determine the ultimate specific creep.

WES UMAT time-dependent material properties model

30. A three-dimensional finite-element model (UMAT) for concrete which includes material aging, creep, shrinkage, and thermal effects has recently been developed for the Corps by Anatech International Corporation working

under contract for the Waterways Experiment Station. An equation of the following series form is used in UMAT to predict creep:

$$C(t,t_0)=\frac{E(t_c)}{E(t_0)}\sum_{i=1}^{m}A_i(1-e^{r_i(t-t_0)})$$

where

$C(t,t_0)$ = creep compliance (specific creep)

t_0 = age of concrete at time of loading, in days

t = age of the concrete, in days

m = number of terms in the series

A_i, r_i = experimentally determined coefficients

t_c = age of loading from which equation coefficients are determined, usually 3 days

$E(t_c)$ = modulus of concrete at the calibration age

$E(t_0)$ = modulus of concrete at the age of loading

31. The term $E(t_c)/E(t_0)$ is known as the age factor. This term is used to account for an age of loading that is different from the age of loading from which the equation constants were determined [5].

CHAPTER IV: EXPERIMENTAL PROGRAM

General

32. This chapter summarizes the equipment, procedures, methods, and results of the experimental phase of the investigation. Described below are the concrete mixture-proportions, test-specimen preparation, test devices, mechanical properties tests, and test results.

Concrete Mixture Proportions

33. Two concrete mixtures, typical for mass concrete applications, were selected for this investigation. These concrete mixtures are designated as mixtures A2 and A11. Both mixtures used Type II, low alkali (LA) portland cement meeting ASTM C 150 and a Class C fly ash meeting ASTM C 618 [11 1]. The fine aggregate was a natural sand composed of blocky, ellipsoidal, and spherical particles. Chert was the primary constituent in sizes larger than 2.36 mm, with quartz predominating in the smaller sizes. The (No. 4 to 3/4-in.) coarse-aggregate was a primarily pale yellowish-brown chert composed of blocky, pyramidal, and tabular particles with rounded edges and corners. Quartz and other miscellaneous particles made up the remainder of the constituents. The (3/4 to 1-1/2-in.*) coarse-aggregate was a crushed stone. It was a speckled medium-light-gray, medium-to-coarse-grained igneous rock classified as syenite. Its composition and textural characteristics were similar to those of granite. Physically the stone was angular with rough surface texture.

34. The mixture proportions for one cubic yard of concrete are shown in Table 1 for both mixtures, all weights are based on saturated-surface-dry aggregate conditions. Table 2 summarizes both mixture characteristics of water-cement ratio (W/C) and fly ash to Portland cement proportion which were calculated by converting the fly ash volume to an equivalent volume of Portland cement.

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* A table of factors for converting non-SI units of measurement to SI (metric) is presented in page vi.

Table 1
Mixture Proportions for One Cubic Yard of Concrete

	Units	Mixture A2	Mixture A11
Water	lb	190.0	173.2
Portland Cement	lb	190.1	232.0
Fly Ash	lb	101.7	124.4
(3/4-in.) Coarse Aggregate	lb	964.3	990.3
(1 1/2-in.) Coarse Aggregate	lb	1176.6	1208.2
Fine Aggregate	lb	1274.8	1200.2
Admixtures			
Air-Entraining	fl. oz.	3.2	1.8
Water-Reducing	fl. oz.	0.0	0.0

Table 2
Mixture Characteristics

Mixture	Water-Cement Ratio	Fly Ash
A2	0.60	40 %
A11	0.45	40 %

Test Specimen Preparation

35. A 10-cubic foot concrete batch was prepared according to ASTM C 192 for each of the two concrete mixtures. Tests were conducted on the fresh concrete to determine slump (ASTM C 143), unit weight (ASTM C 138), air content (ASTM C 231), and time of setting (TOS) (ASTM C 403). The results of the tests conducted on the fresh concrete are shown in Table 3. Specimens were prepared according to ASTM C 192 from both mixtures A2 and A11 for performing a series of early-age material properties tests, which will be described in detail in the next section. The specimens were cured, until time of testing, in a moist-curing room meeting the specifications of ASTM C 511 [11 j].

Table 3
Results of Tests on Fresh Concrete

Mixture Designation	Slump in.	Unit Weight lb/ft^3	Air Content %	Time of Setting, hours
A2	2-1/2	142.4	5.5	11.33
A11	3	143.2	5.2	17.00

Mechanical Properties Tests

36. A series of early age material properties tests was conducted on hardened concrete specimens from both concrete mixtures (A2 and A11). Unconfined compressive strength tests, elastic modulus tests, and creep tests were conducted at five ages of loading (18 hours, 1 day, 3 days, 7 days, and 14 days).

Unconfined Compression Tests

37. Unconfined compression tests were conducted in accordance with ASTM C 39 [11 a] (Appendix A) at the five ages shown above to provide data on strength as a function of time. The specimens tested were 6 in. in diameter by 12 in. in length. The ends of the specimens tested at ages of one day or less were capped with a neat-cement cap, while the specimens tested at ages greater than one day were capped with sulfur capping compound. Capping of the ends of the specimens was necessary to provide plane and parallel loading surfaces in accordance with ASTM C 39 [11 a]. The capped specimens were tested in a 440-kip-capacity universal testing machine by applying a uniaxial compressive force at 35 psi/sec until the specimen failed. The maximum recorded applied force was then divided by the original cross-sectional area to determine the unconfined compressive strength of the specimen. The results of the compressive strength tests are shown in Table 4.

Table 4
Compressive Strength Data for Mixtures A2 and A11

Mixture	Age at Loading, t_o	Compressive Strength, psi
A2	18 Hours	177
A2	1 Day	210
A2	3 Days	499
A2	7 Days	730
A2	14 Days	1010
A11	18 Hours	375
A11	1 Day	535
A11	3 Days	1115
A11	7 Days	1705
A11	14 Days	2425

Modulus of Elasticity Tests

38. The modulus of elasticity of both mixtures at the various ages of loading was determined from the initial-loading phase of the creep tests. Although at very early ages (three days or less) the mixtures exhibited limited linear-elastic compressive behavior, estimates of elastic modulus at very early ages are necessary for calibrating the material models to be investigated in Chapter 5. Thus, a tangent modulus was determined from the stress-strain data obtained upon initial loading of a compressive creep specimen. This initial loading phase of the creep test was usually conducted in less than two minutes total elapsed time; however, some creep occurred during the initial loading phase, particularly at the earlier ages of loading. Any creep strains which occurred during the initial loading phase were subtracted from the elastic strains in calculating the elastic modulus. The results of the elastic modulus tests are shown in Table 5.

Table 5
Modulus of Elasticity Data for Mixtures A2 and All

Mixture	Age at Loading, t_o	Elastic Modulus 10^6 psi
A2	18 Hours	0.35
A2	1 Day	0.42
A2	3 Days	2.03
A2	7 Days	2.58
A2	14 Days	2.97
All	18 Hours	1.05
All	1 Day	1.37
All	3 Days	2.88
All	7 Days	3.82
All	14 Days	4.50

Compressive Creep Tests

39. Creep is most simply defined as time-dependent deformation induced by sustained load. Although concrete can exhibit changes in deformation with no applied load due to shrinkage (both drying and sealed), creep is normally assumed to be the deformation in excess of shrinkage strains and elastic strains. It is generally agreed that the creep response of concrete is fundamentally governed by the movement of water under load and its effect on continued hydration and strength development.

40. Upon initial application of load at time t_o, the material response is primarily elastic, but may include a non-elastic component. The nominal elastic strain is governed by the elastic modulus at time t_o. These basic relationships are shown in Figure 3. It is common practice to ignore the change in elastic modulus with time. Shrinkage of the creep specimen is measured by monitoring the deformation of identically prepared unloaded specimens. Thus, the creep strains are calculated from the total measured strains as follows:

$$\epsilon_{creep}=\epsilon_{total}-\epsilon_{elastic}-\epsilon_{shrinkage}$$

41. Using these concepts, creep tests were conducted according to ASTM C 512 [11 k] and modified to include continuous data acquisition by computer. The specimens tested were 6 in. in diameter by 16 in. in length. The creep specimens were cast with the longitudinal axis in a horizontal plane in steel forms and were subjected to external vibration to provide adequate consolidation as shown in Figure 4. These forms accommodated Carlson strain gages placed at the center of the specimens oriented along the longitudinal axis of the cylinder as shown in Figure 5. A general discussion of Carlson strain gages is presented in Appendix C. Steel bearing plates were attached to the ends of the specimen by embedded mechanical anchors. These plates provided a smooth plane surface for applying the compressive force. A bituminous moisture barrier was applied to the surface of the creep specimen immediately after the forms were removed to prevent moisture from entering or leaving the specimen as shown in Figure 6.

42. The apparatus used to perform the creep tests was a hydraulic loading frame designed to maintain a constant stress by means of a gas pressure regulator in series with a gas and oil accumulator and hydraulic ram. The desired applied stress was set by means of the gas pressure regulator. The test device accommodated two specimens loaded in series. For each mixture two control cylinders were also monitored to determine the strains not associated with the applied loads as shown in Figure 7. Photos of a typical creep testing device are shown in Figure 8 and Figure 9. The creep specimens were loaded to 40 percent of the unconfined compressive strength at the age of loading as determined from unconfined compressive tests on companion 6-in by 12-in cylinders. The applied stress was maintained until a minimum age of 28 days was attained with the exception of the 7-day test on mixture A11. That particular test was terminated approximately 7 days after loading due to a malfunction of the creep test device. The following measurements were recorded using a digital data acquisition system:

a. Applied stress, by pressure transducers located in the gas pressure regulator output line;

b. Strain and temperature in the loaded specimen, by Carlson strain gages embedded in the center of the specimen;

c. Strain and temperature in the control specimen, by Carlson strain gages embedded in the center of the specimen and

d. Time, by an internal clock in the computer data-acquisition unit.

43. The recorded data from the creep tests are shown in Appendix D. The data from the creep tests were reduced as specified in ASTM C 512. The procedure requires that the strains which occur during the initial loading and the strains recorded by the shrinkage compensation cylinders be subtracted from the measured strains. These corrected strains were then divided by the average sustained stress to obtain specific creep:

$$C(t, t_o) = \frac{\epsilon_{creep}}{\sigma_{applied}}$$

These data are shown in Figures 10 through 19.

44. Several observations can be made about the creep data. The creep strain per unit stress decreases with increasing age of loading. This decrease of the creep response is related to the continuing increase in modulus of elasticity and strength due to continuing hydration of the cement. The specimens loaded at very early ages (1 day or less) exhibited high levels of creep very early after the application of the stress. It is likely that this is due to the amount of free water which is able to move throughout the matrix at this early age.

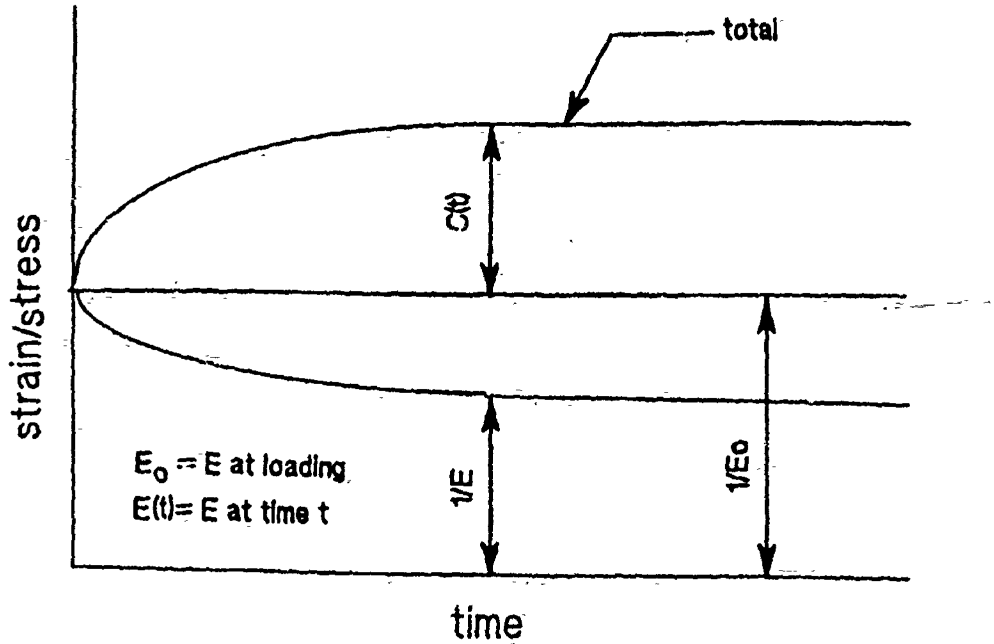

Figure 3. Basic specific creep relationships

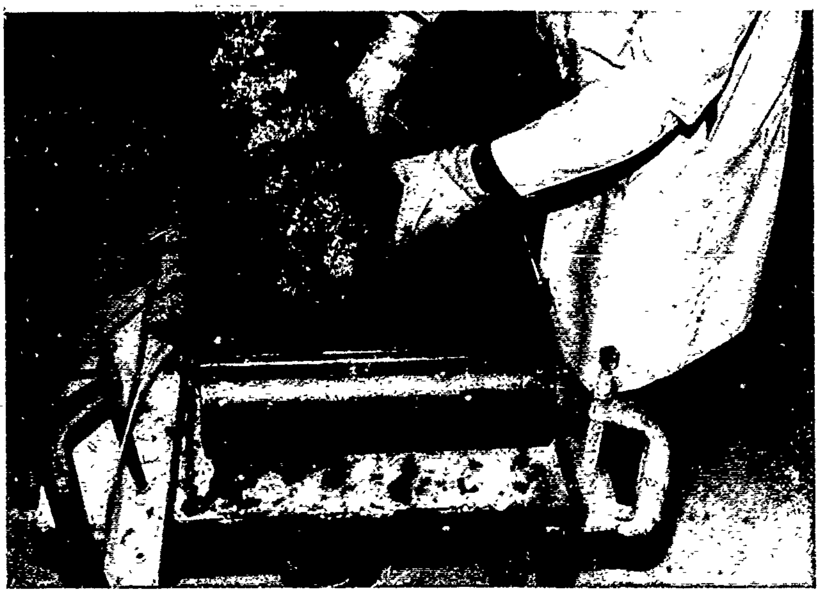

Figure 4. Preparation of creep test specimens using vibratory compaction table

Figure 5. Steel mold for creep specimens with Carlson Strain gage installed

Figure 6. Application of Bituthane moisture barrier to hardened creep specimen

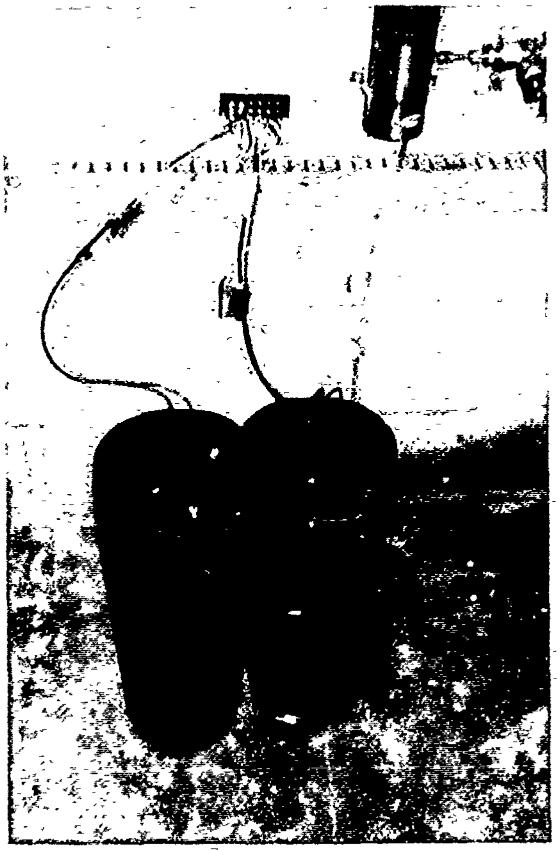

Figure 7. Creep test control cylinders

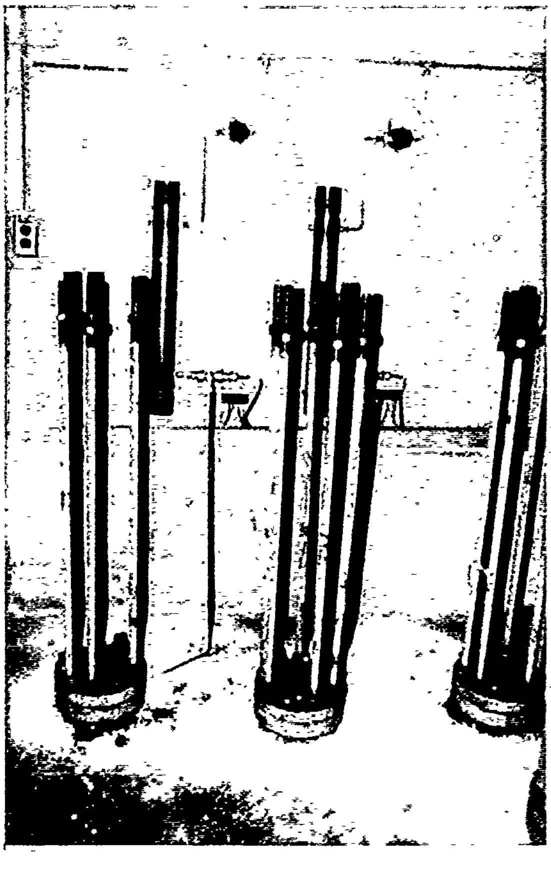

Figure 8. Creep test devices prior to loading of the test specimens

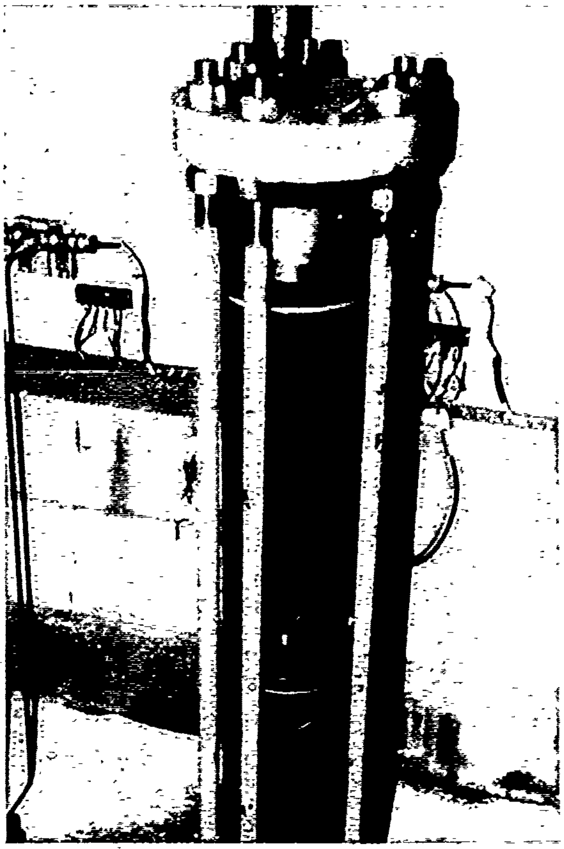

Figure 9. Creep test device complete with loaded creep cylinders

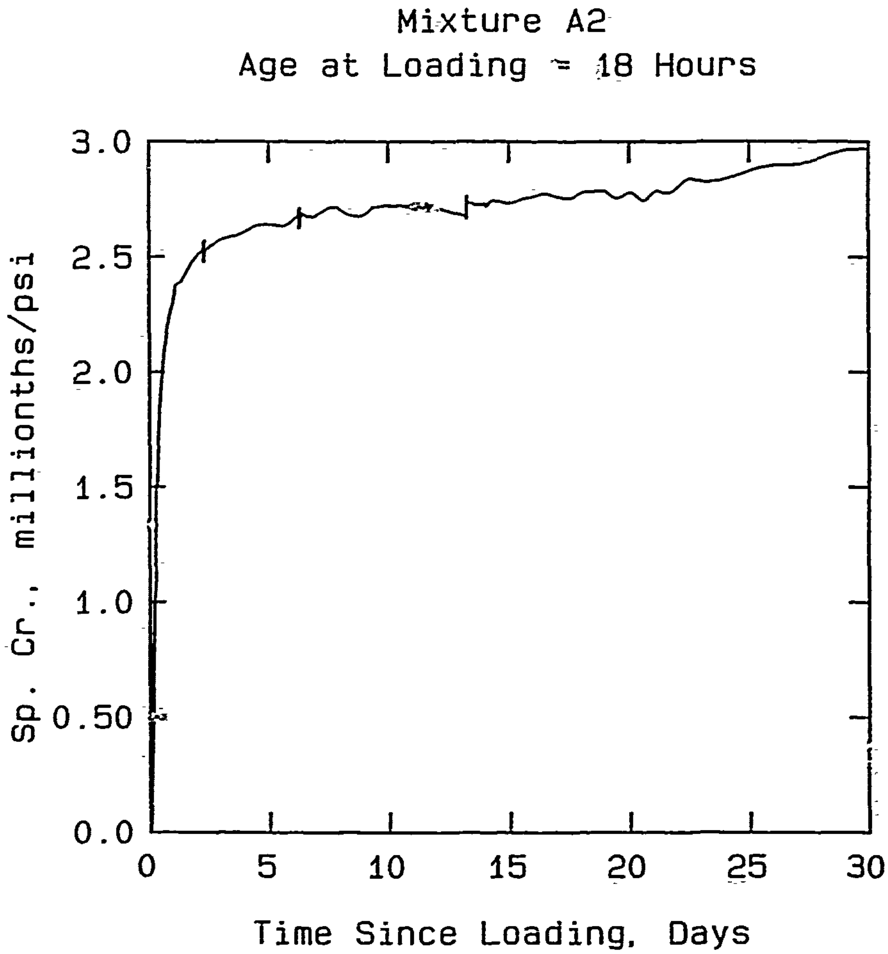

Figure 10. Specific creep versus time since loading from 18-hour test on mixture A2

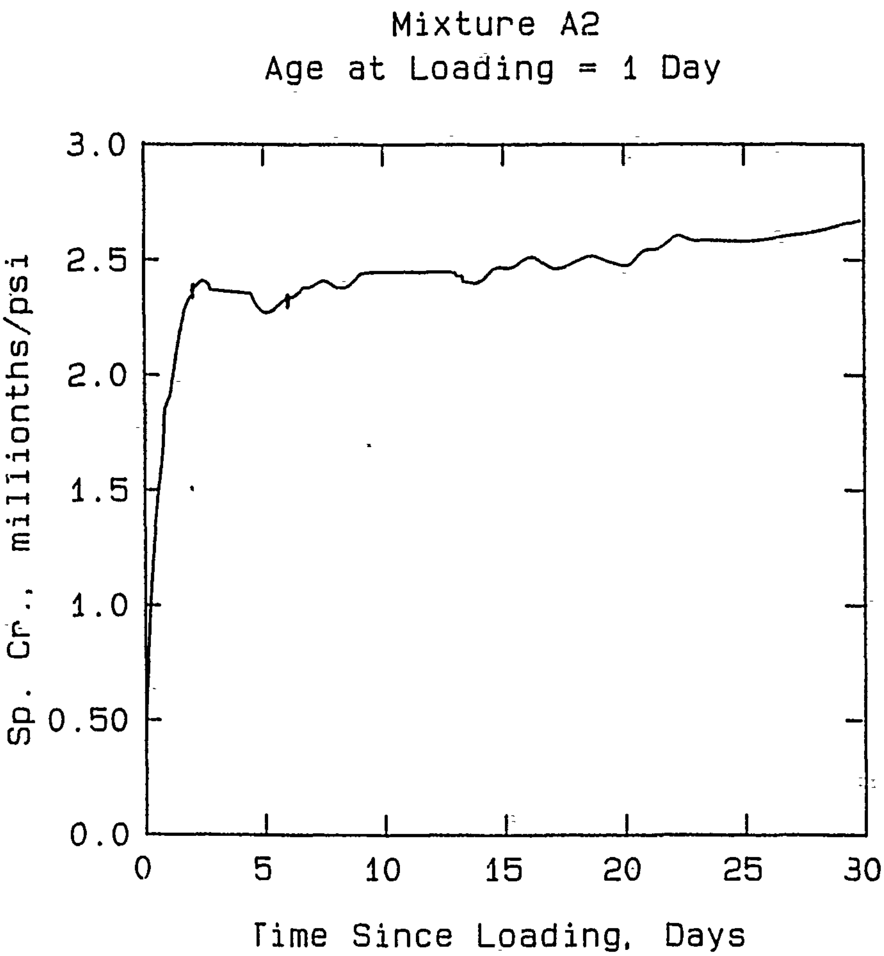

Figure 11. Specific creep versus time since loading from 1-day test on mixture A2

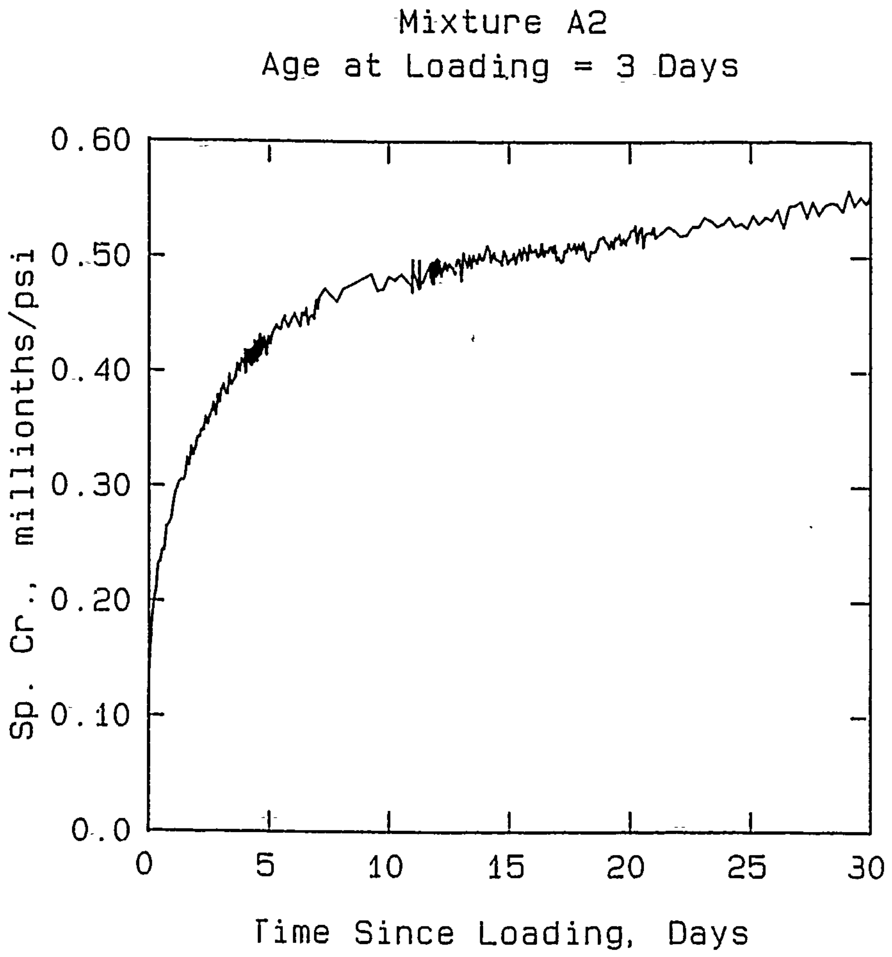

Figure 12. Specific creep versus time since loading from 3-day test on mixture A2

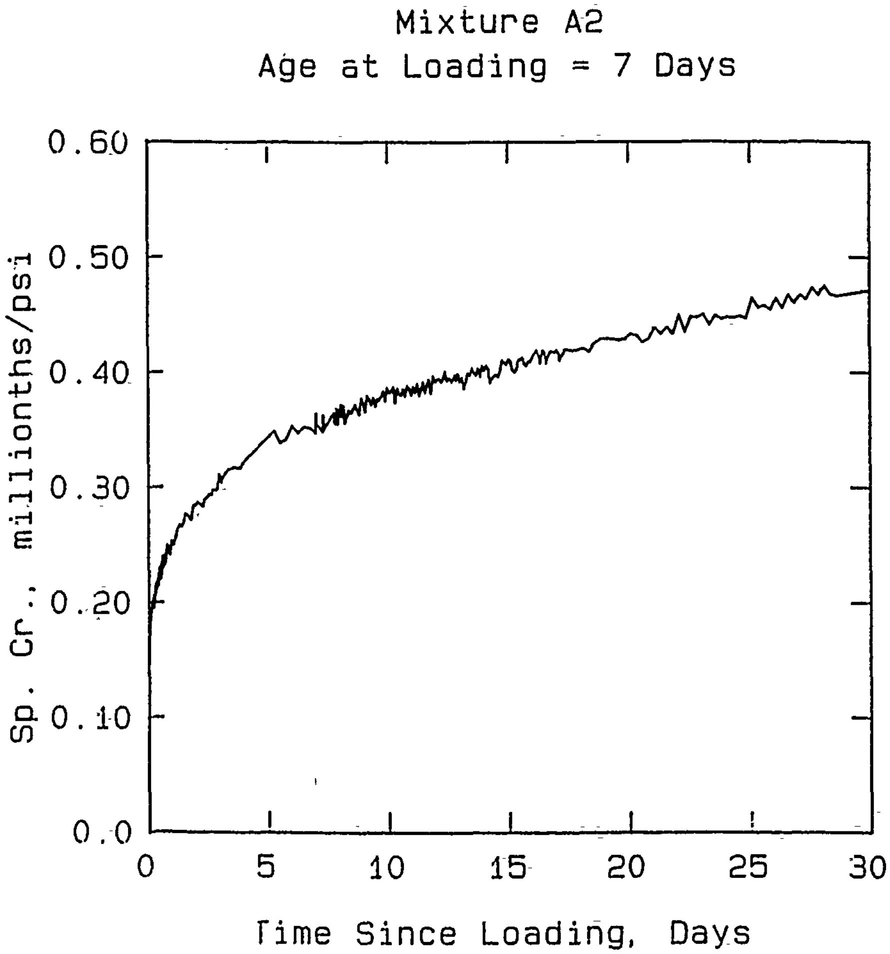

Figure 13. Specific creep versus time since loading from 7-day test on mixture A2

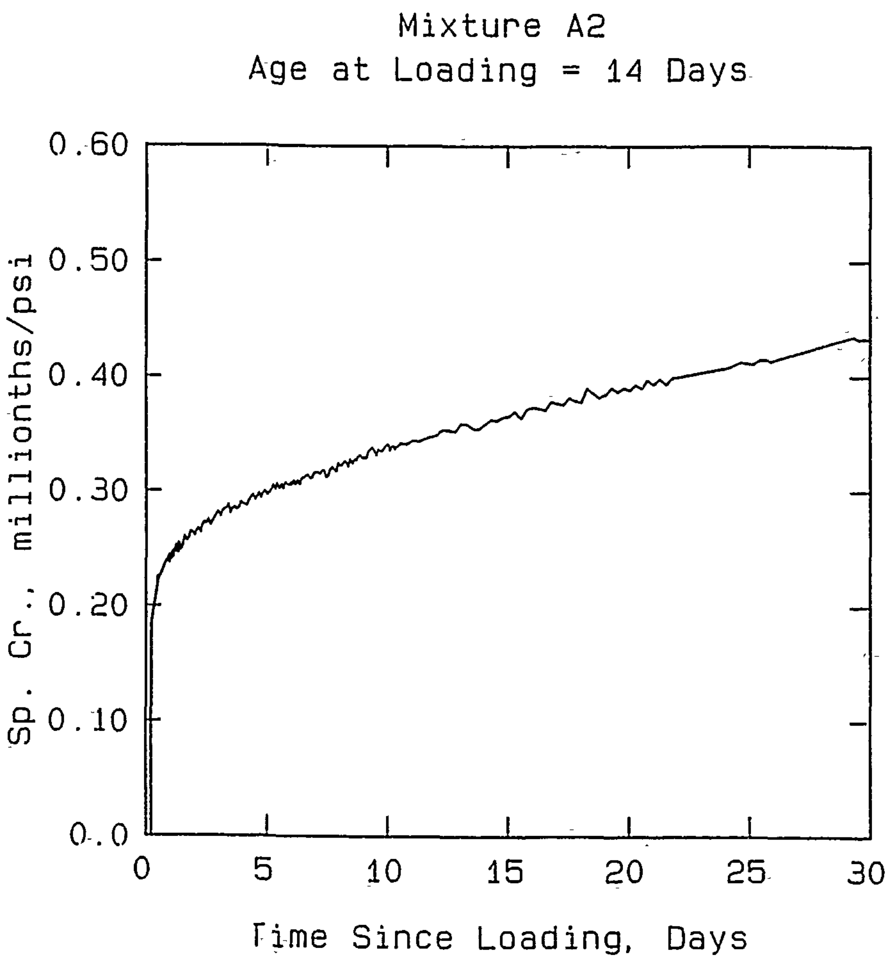

Figure 14. Specific creep versus time since loading from 14-day test on mixture A2

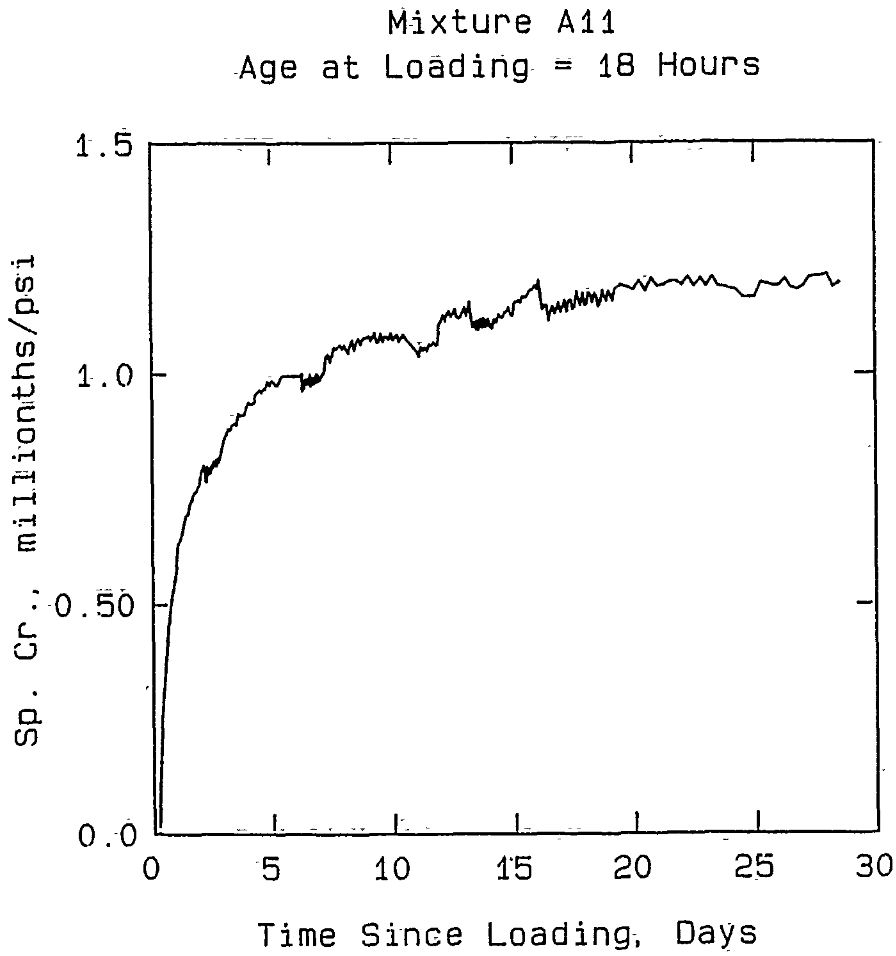

Figure 15. Specific creep versus time since loading from 18-hour test on mixture A11

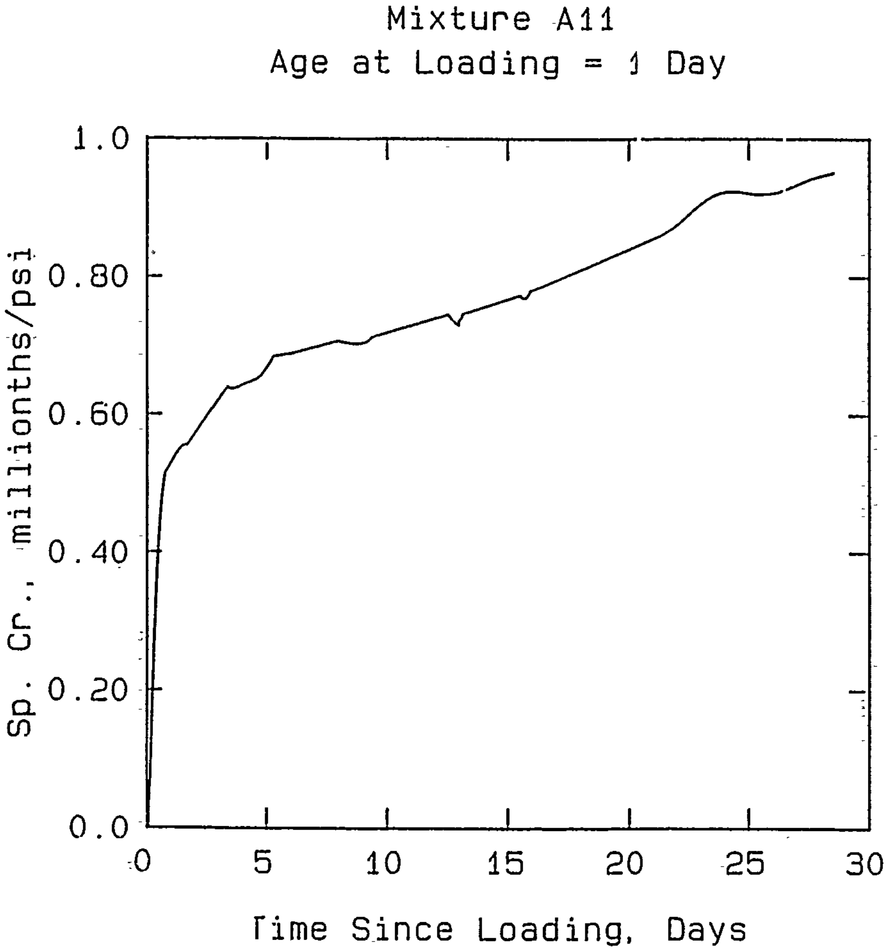

Figure 16. Specific creep versus time since loading from 1-day test on mixture A11

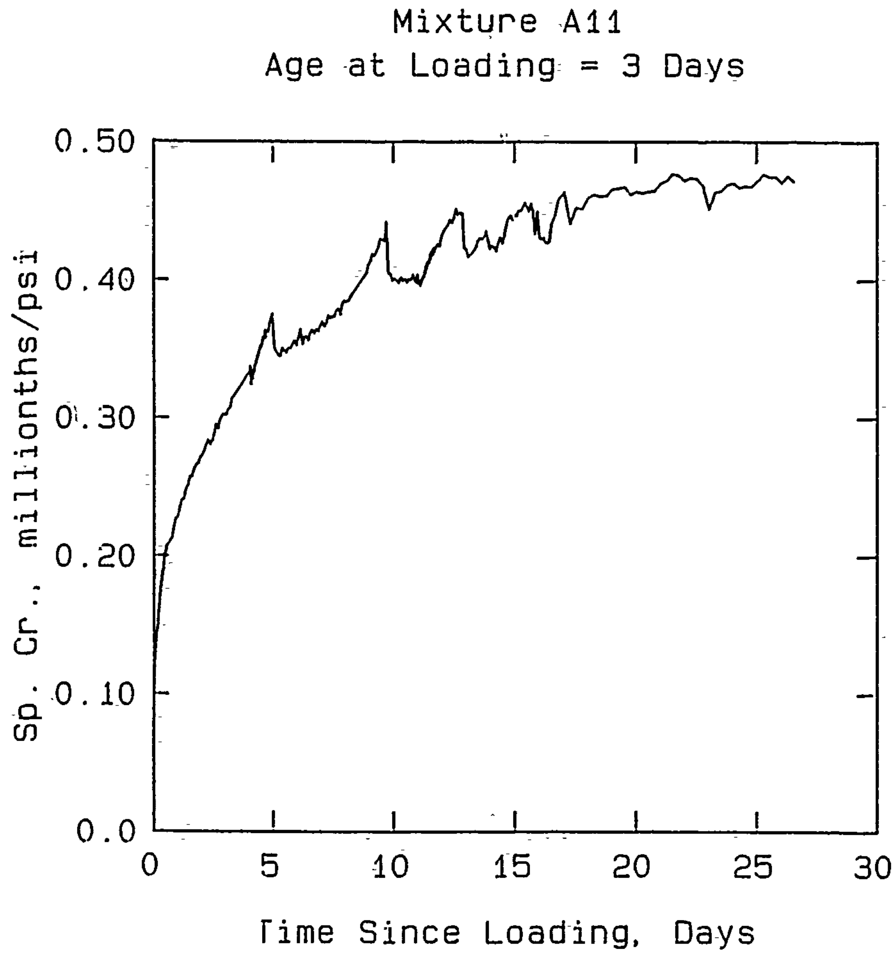

Figure 17. Specific creep versus time since loading from 3-day test on mixture A11

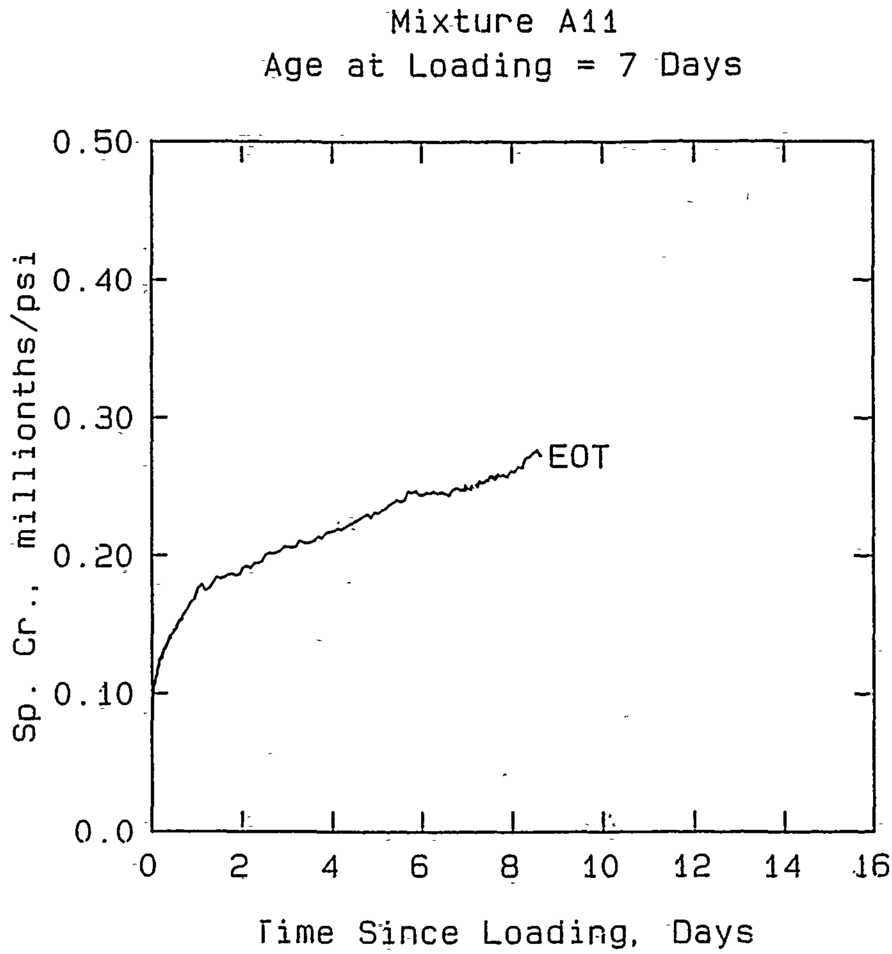

Figure 18. Specific creep versus time since loading from 7-day test on mixture A11

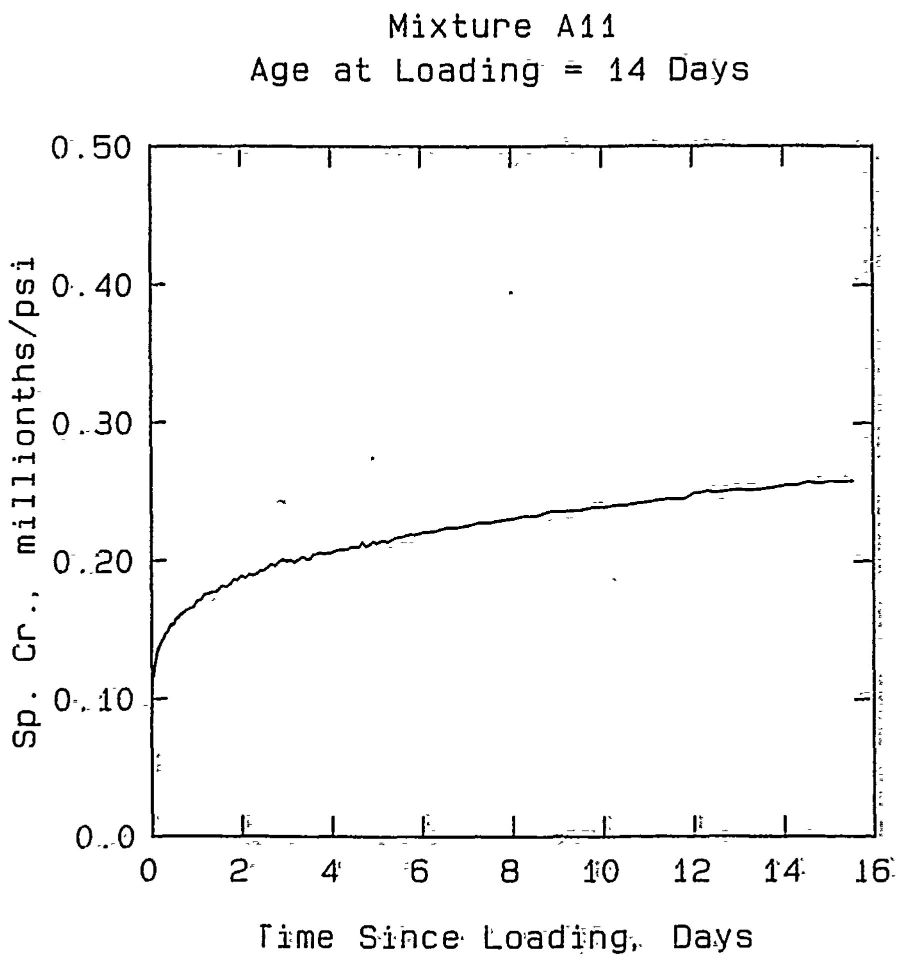

Figure 19. Specific creep versus time since loading from 14-day test on mixture A11

CHAPTER V: ANALYSIS

General

45. In this chapter the results of the experimental program are used to calibrate, verify, and evaluate the effectiveness of currently used strength-modulus relationships and three viscoelastic material models for predicting mechanical response of concrete at early ages. After the models were selected, simple trial and error procedures were used to calibrate the parameters of each model. The models will be used to predict mechanical response of concrete under the test conditions. The predictions will be evaluated in light of the test data. A sign convention of compression positive is used throughout the analysis.

Selection of Mechanical Properties Models

46. Two common simple models used to predict the strength and elastic modulus as functions of time were selected for comparison with early age mechanical properties test data. These models are based on least-squares fits of test data in a log-time domain. Three of the viscoelastic concrete creep models presented in Chapter 5 were selected for comparison with early age mechanical properties test data. These models are the ACI creep formula, the WES UMAT creep equation, and the Bazant Sinh-Double Power Law creep formulation.

Calibration of Creep Model Parameters

ACI creep equation

47. ACI recommends the following equation for predicting creep of moist-cured concrete at any time:

$$C(t, t_0) = \frac{(t-t_0)^{\Psi}}{10+(t-t_0)^{\Psi}} C_{\infty}(t_0)$$

Where $C(t,t_o)$ represents the specific creep at any age t caused by a uniaxial stress applied on concrete at age t_o. ACI recommends a value of 0.6 for the exponent ψ. Predictions were made using the recommended value of ψ=0.6 and with the maximum value of ψ=1. $C_\infty(t_o)$, the ultimate specific creep, was determined from the maximum specific creep value from each age of loading for both mixtures. These values are shown in Table 6.

Table 6
ACI Ultimate Specific Creep for Mixtures A2 and A11

Mixture	Age at Loading, t_o	$C_\infty(t_o)$
A2	18 Hours	2.931
A2	24 Hours	2.624
A2	3 Days	0.542
A2	7 Days	0.472
A2	14 Days	0.427
A11	18 Hours	1.213
A11	24 Hours	0.947
A11	3 Days	0.471
A11	7 Days	0.276
A11	14 Days	0.258

WES UMAT creep equation

48. An equation of the following series form is used in UMAT to predict creep:

$$C(t,t_0) = \frac{E(t_c)}{E(t_0)} \sum_{i=1}^{m} A_i \left(1 - e^{r_i(t-t_0)}\right)$$

where:

$C(t,t_0)$ = creep compliance (specific creep)

t_0 = age of concrete at time of loading, in days

t = age of the concrete, in days

m = number of terms in the series

A_i, r_i = experimentally determined coefficients

t_c = age of loading from which equation coefficients are determined

$E(t_c)$ = modulus of concrete at the calibration age

$E(t_0)$ = modulus of concrete at the age of loading

49. The coefficients A_i and r_i were determined from fits of the equation to the experimental test data at an age of loading of 3 days and are shown in Table 7. From previous work with this model the 3-day test has proven to be an effective calibration age for the UMAT equation [5]. For the purposes of this investigation a three-term series will be used.

Table 7
UMAT Creep Equation Coefficients for Mixtures A2 and A11

Mixture	A_1	r_1	A_2	r_2	A_3	r_3
A2	0.1989	-0.0764	0.1487	-0.8831	0.2166	-1.300
A11	0.1308	-0.0589	0.1965	-0.1892	0.1656	-1.766

Bazant Sinh-Double Power Law (SDPL)

50. The Bazant SDPL specific creep function $C(t,t_o)$ represents the strain per unit stress at any age t caused by a uniaxial stress applied on concrete at age t_o.

$$C(t, t_0) = \frac{\psi_0}{E_0} \sinh^{-1}\xi$$

where:

$$\xi=\psi_1(t_0^{-m}+\alpha)(t-t_0)^n$$

E_o represents the elastic modulus at the time of loading and ψ_o, ψ_1, α, n, and m are five constants determined from trial-and-error fits of $C(t,t_0)$ to calibration test data. Bazant suggests that the parameter ψ_1 be set equal to 1 in order to reduce the number of constants to four. Acceptable results were produced using this suggestion in the initial presentation of the SDPL. To provide an effective comparison with the UMAT equation, 3-day test data were also used to obtain the calibration values for the SDPL equation constants. The final values for these constants are shown in Table 8.

Table 8
SDPL Creep Constants for Mixtures A2 and A11

Mixture	ψ_o	ψ_1	α	n	m
A2	0.9	1	0.027	0.194	0.21
A11	1.1	1	0.020	0.194	0.20

Discussion of Test Data and Models

51. In the following sections a discussion of the test results and their comparison with model predictions will be presented. As with the previous data presentations, a sign convention of compression positive will be used.

Compressive strength and modulus of elasticity

52. For each concrete mixture, two plots are shown: compressive strength versus the logarithm of time (in days) and modulus of elasticity versus the logarithm of time. These plots are shown in Figures 20 through 23.

53. Compressive strength and modulus of elasticity are roughly linear over the period from time of final setting to 14 days when plotted against the logarithm of time. Therefore, on each plot, equations of the form

$$f_c(t)=a_0+a_1\log(t)$$

and

$$E(t)=b_0+b_1\log(t)$$

have been fit to the data using the method of least squares where strength is calculated in psi and modulus is calculated in psi X 10^6 , while a_0, a_1, b_0 and b_1 are constants determined in the least-squares curve fit. The results of the least squares fits are shown on each plot and in Table 9.

Table 9
Strength and Modulus Equation Constants

Mixture	a_0	a_1	b_0	b_1
A2	219.3	551.1	0.67	2.17
A11	352.6	1244.1	1.25	2.76

54. The ACI Building Code 318-90 gives the following equation for the static modulus of elasticity (in psi) of concrete:

$$E_{ct}=57000\sqrt{(f'_c)_t}$$

where $(f'_c)_t$ is the compressive strength in psi at time t. The relationships between modulus of elasticity and compressive strength for both mixtures are shown in Figures 24 and 25. These data indicate that a relationship exists between compressive strength and modulus of elasticity, even at very early time. It appears, however, that over the time period from time of final setting to 14 days, this relationship may not be well-represented by a linear function in the modulus of elasticity-square root compressive strength plane. For purposes of comparison, the ACI 318 equation has also been shown in Figures 24 and 25. Although this equation was not intended for use with the independent variable as any value other than the 28-day compressive strength (f'_c), it is instructive to compare the results from the equa ...n to early-time data. As can be seen in Figures 24 and 25, the ACI 318 equation generally under predicts the modulus of elasticity at early times. Therefore, it appears that this relationship should not be used by structural analysts to predict modulus of elasticity from compressive strength at ages less than 28 days for mass concretes.

Creep Data and Model Predictions

55. For both of the concrete mixtures, composite plots are shown of specific creep versus time since loading from the creep test data, the ACI Equation, the Sinh-Double Power Law, and the UMAT Creep Equation for all five ages of loading. These plots are shown in Figures 26 through 35.

56. As expected, the very early age creep tests exhibit the greatest amount and rate of creep. Mixture A2 clearly creeps more than Mixture All. This was expected due to the higher water-cement ratio and consequent lower strength and modulus of A2 (W/C=0.60) as compared to All (W/C=0.45). All three creep models agreed with this general behavior at all ages of loading. However, the agreement of the models stops at this point.

57. The ACI equation, with either of the two exponent values (0.6 or 1.0), grossly underpredicts creep for both mixtures at all ages of loading for the duration of the test. This underprediction can be attributed to the nature of the test data from which the ACI equation was developed. The majority of test data used in developing the ACI creep equation came from tests on structural concrete loaded at later ages. The emphasis of the development was to provide an equation by which long-term structural deflections could be calculated. Because of this, early-age effects were not considered and are not adequately modeled. The ACI equation performs well the purpose for which it was intended; however, since its performance at early ages is less than desirable the following discussions of test data will primarily address the SDPL and UMAT equations.

58. The SDPL and UMAT creep predictions for the 18-hour tests agreed with the general form of the data for both mixtures. The SDPL equation

clearly overpredicted the creep response throughout the entire 18-hour test for both mixtures. However, the SDPL prediction does follow the response of mixture A11 more closely than that of mixture A2 for the 18-hour test. The UMAT equation produced a better overall prediction of the 18-hour tests for both mixtures. During the early times after application of load the UMAT equation underpredicted creep response, while during the later stages of the 18-hour tests the UMAT equation overpredicted creep response for both mixtures.

59. The UMAT equation produced the closest prediction of creep response for 1-day test on both mixtures. Again, the SDPL equation overpredicted creep for the majority of the 1-day testing period. The UMAT equation underpredicted creep response for the first portion of the test and then overpredicted creep during the later stages of the test.

60. As was expected, the prediction of both the UMAT and SDPL equations are very good at the 3-day age of loading for both mixtures. The equation constants for both the UMAT and SDPL equations were determined from trial and error fits to the test data at the 3-day age of loading. The trends seen in the earlier tests are still evident in the 3-day tests for both mixtures. The SDPL equation overpredicts creep response during the early test stages and very closely approximates the creep response during the later stages of the 3-day tests for both mixtures. For both mixtures, the UMAT equation provides the closest prediction with a minimal amount of underprediction at early times with a very close approximation of the creep response during the later stages of the 3-day tests.

61. The predictions of both the UMAT and the SDPL equations for the 7-day and the 14-day tests for both mixtures exhibit the same general features. The UMAT equation predicted the greatest amount of creep for both concrete mixtures. Both equations underpredicted the creep response of mixture A2 for the 7-day and the 14-day tests. As noted earlier, the mixture A11 7-day test was terminated early due to a malfunction of the test device. In general the predictions of both equations were less accurate for the 7-day and 14-day tests than for the earlier ages of loading for both concrete mixtures.

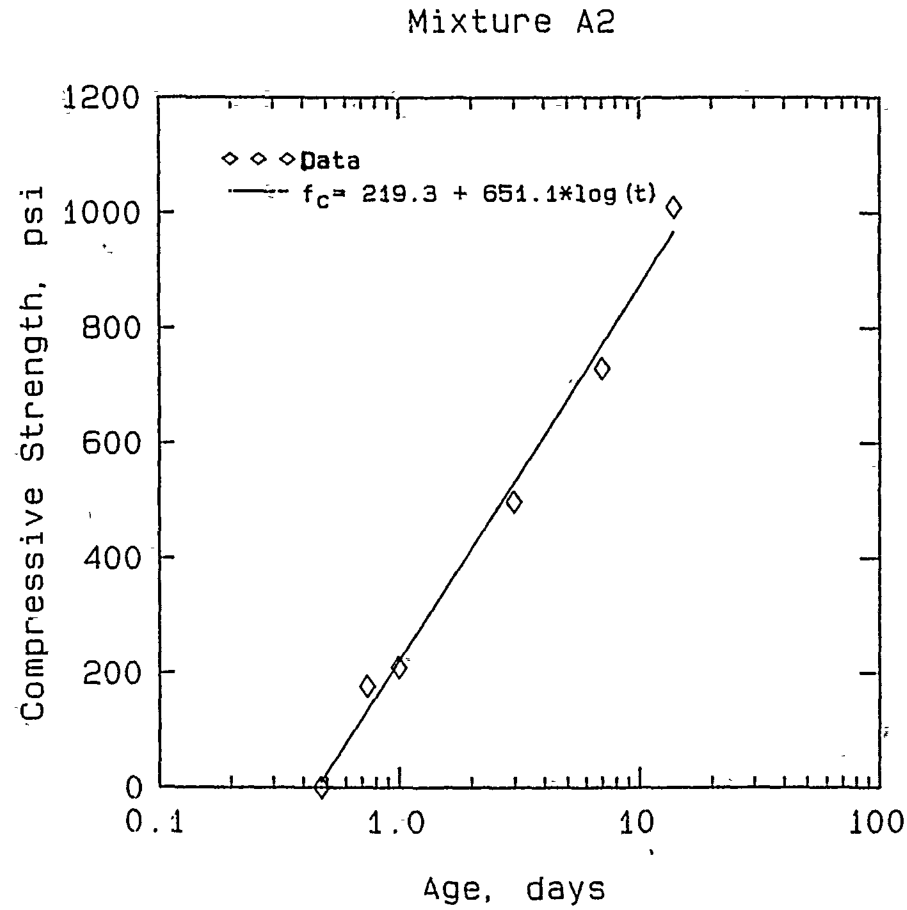

Figure 20. Compressive strength versus age for mixture A2

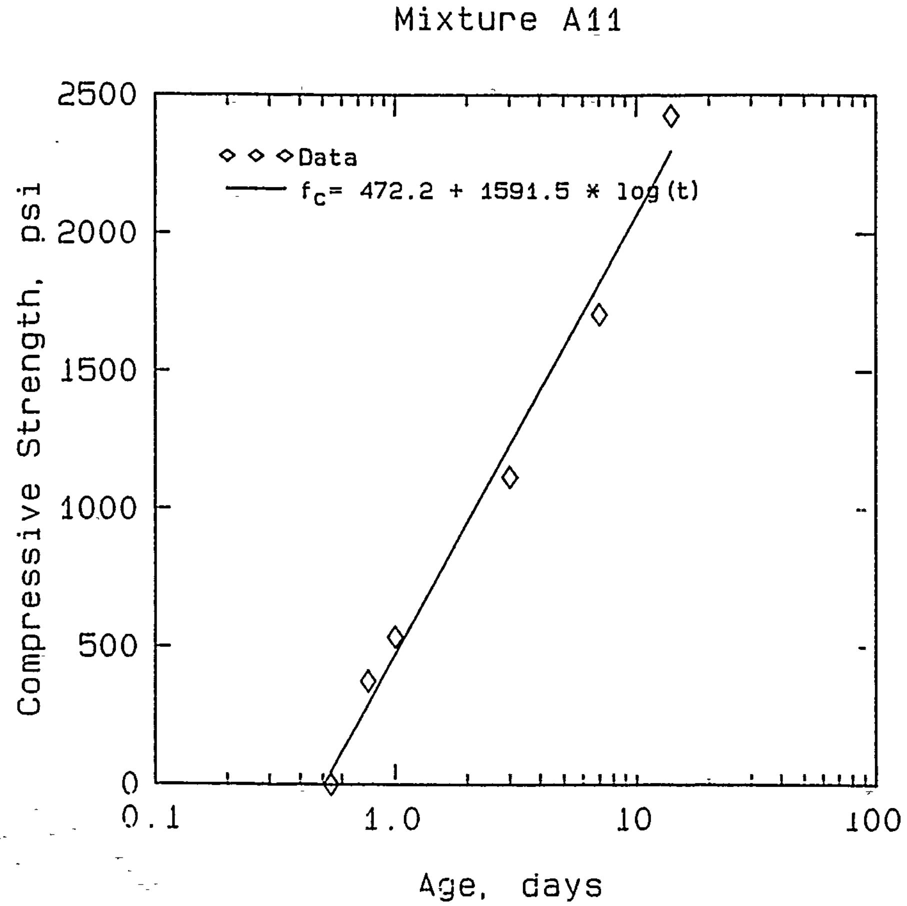

Figure 21. Compressive strength versus age for mixture A11

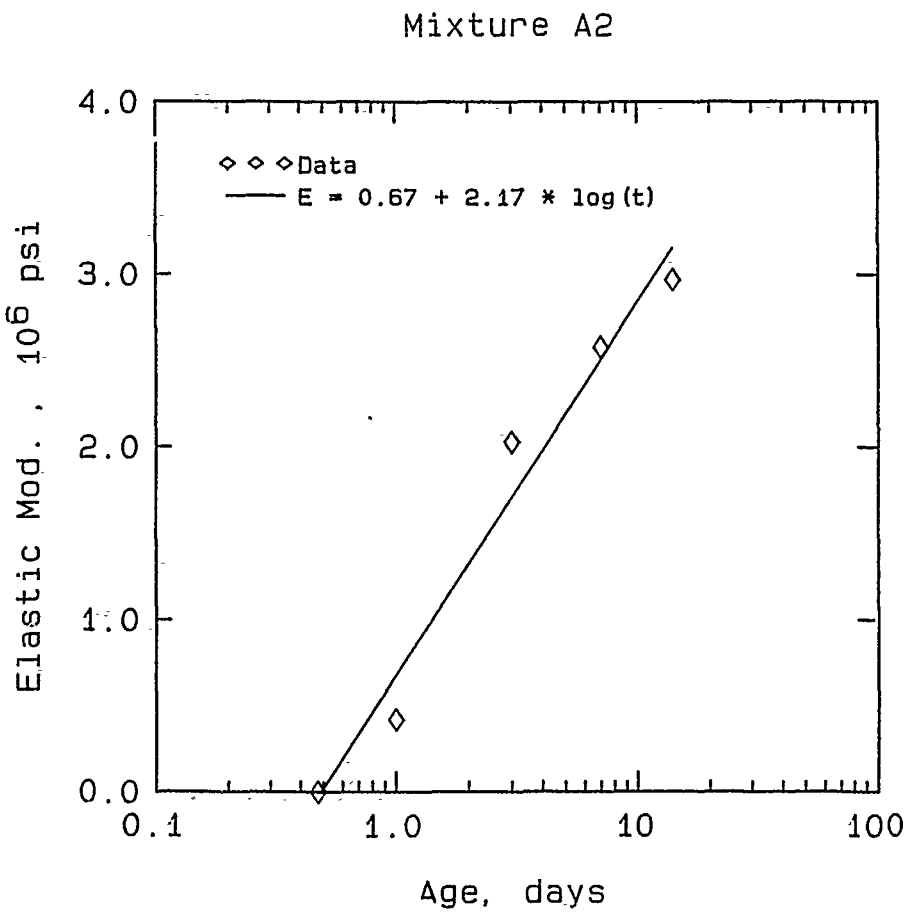

Figure 22. Elastic modulus versus age for mixture A2

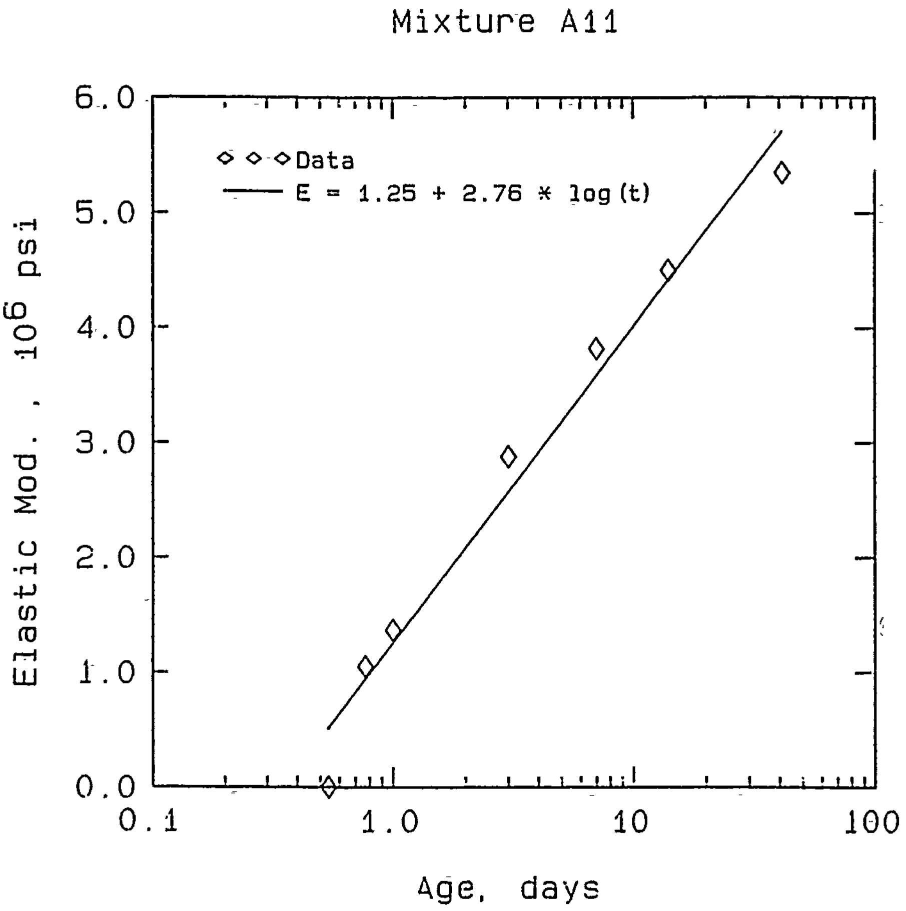

Figure 23. Elastic modulus versus age for mixture A11

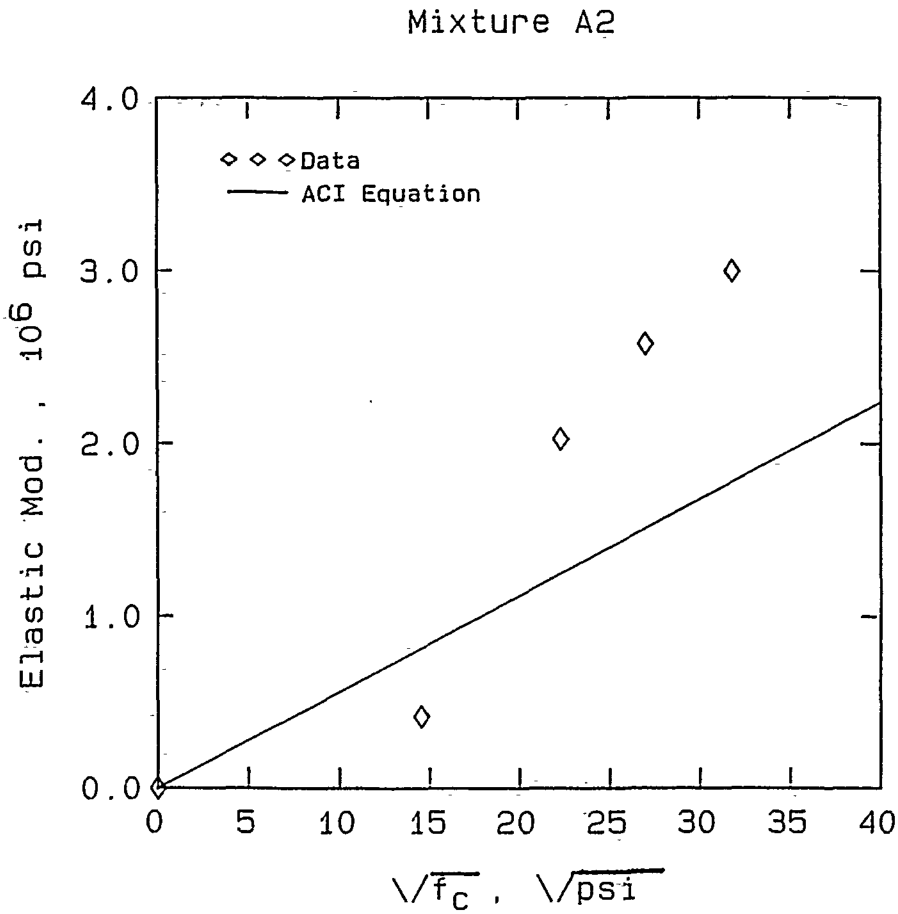

Figure 24. Elastic modulus versus square root of compressive strength for mixture A2

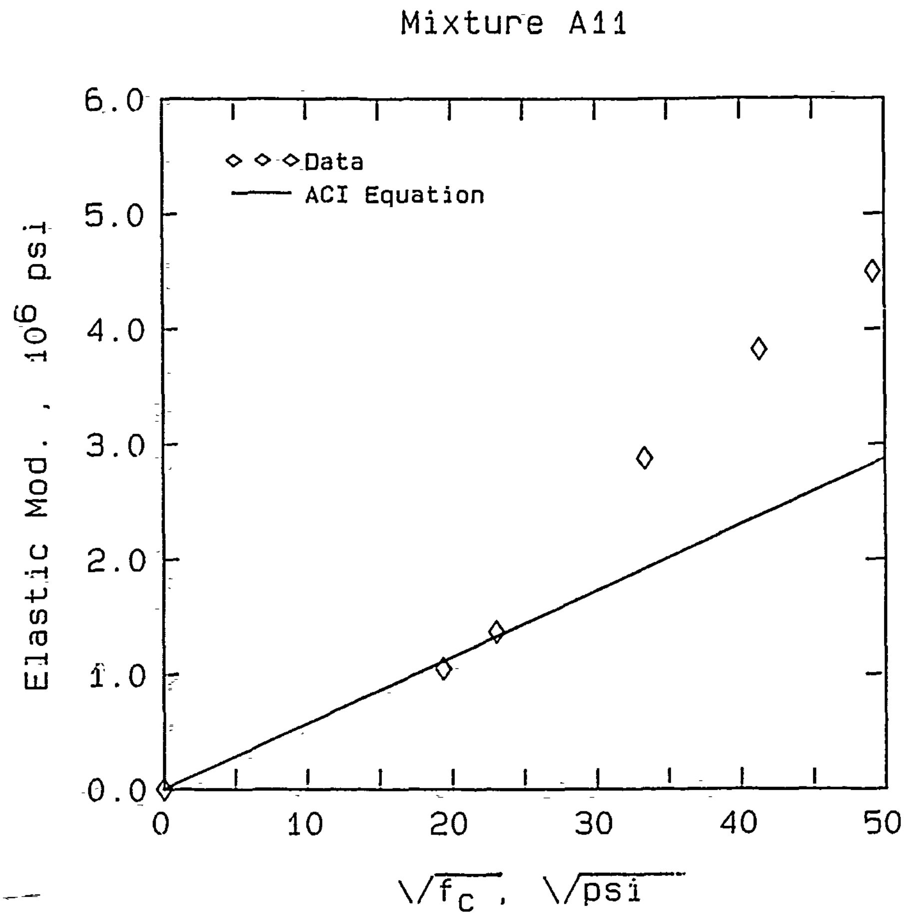

Figure 25. Elastic modulus versus square root of compressive strength for mixture All

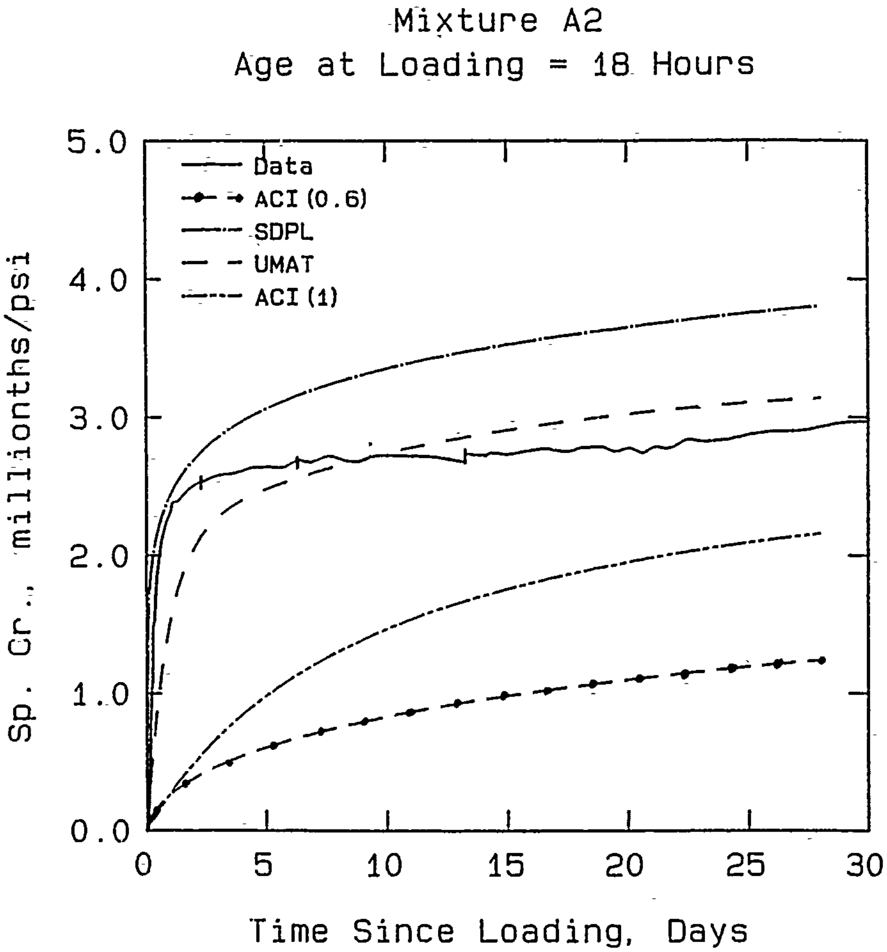

Figure 26. Comparison of test data and creep model predictions from 18-hour test on mixture A2

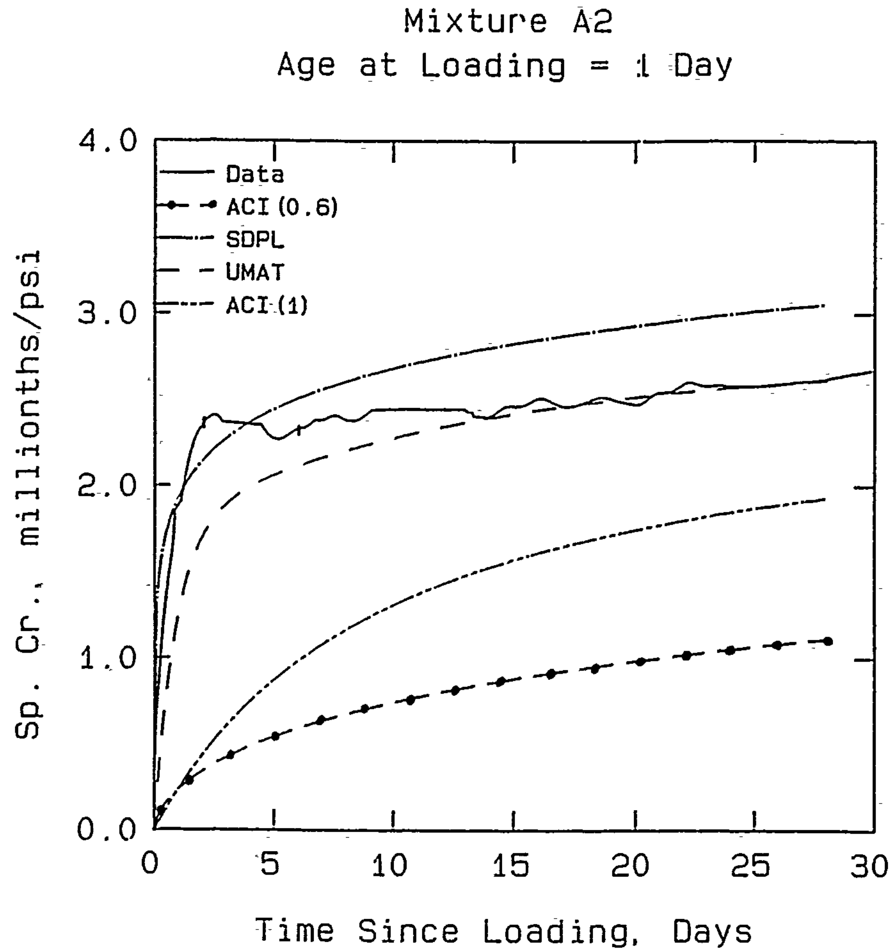

Figure 27. Comparison of test data and creep model predictions from 1-day test on mixture A2

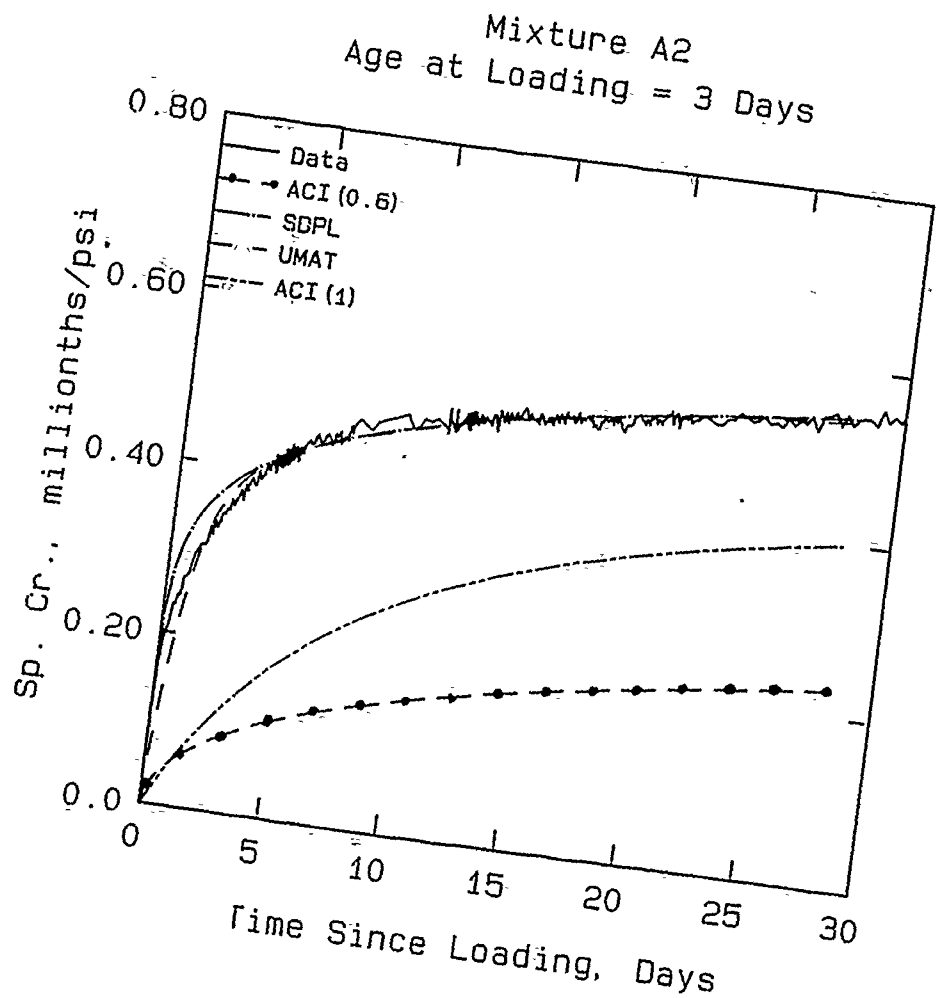

Figure 28. Comparison of test data and creep model predictions from 3-day test on mixture A2

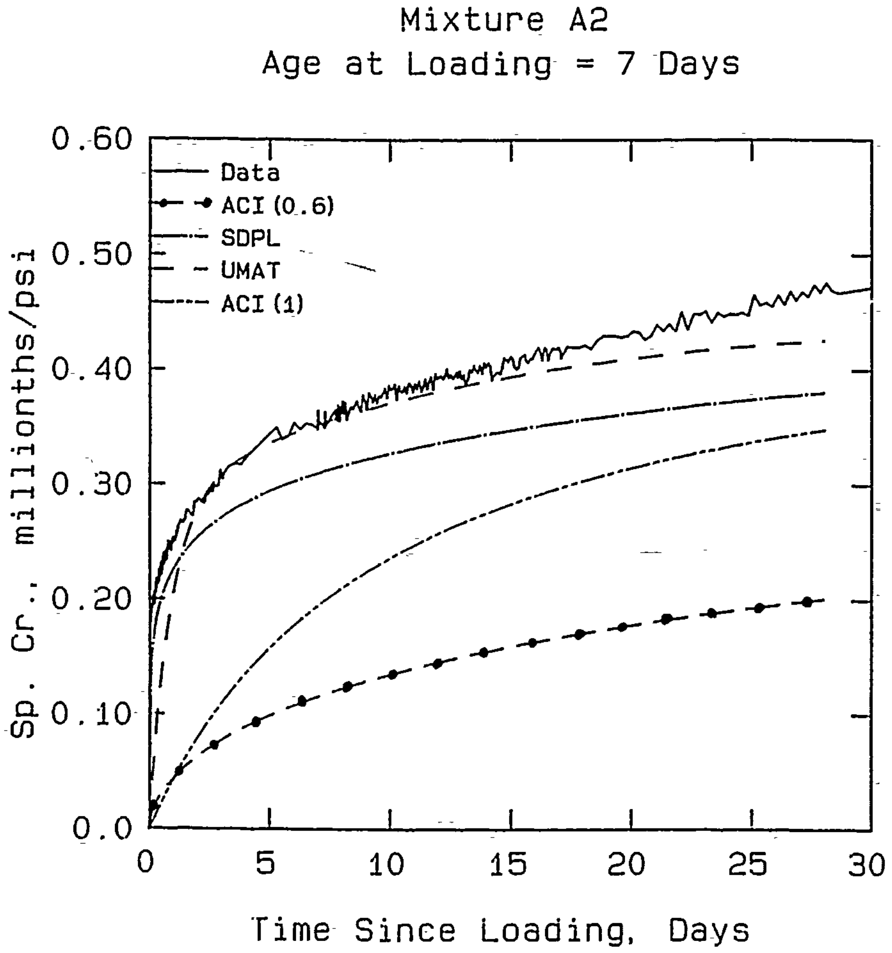

Figure 29. Comparison of test data and creep model predictions from 7-day test on mixture A2

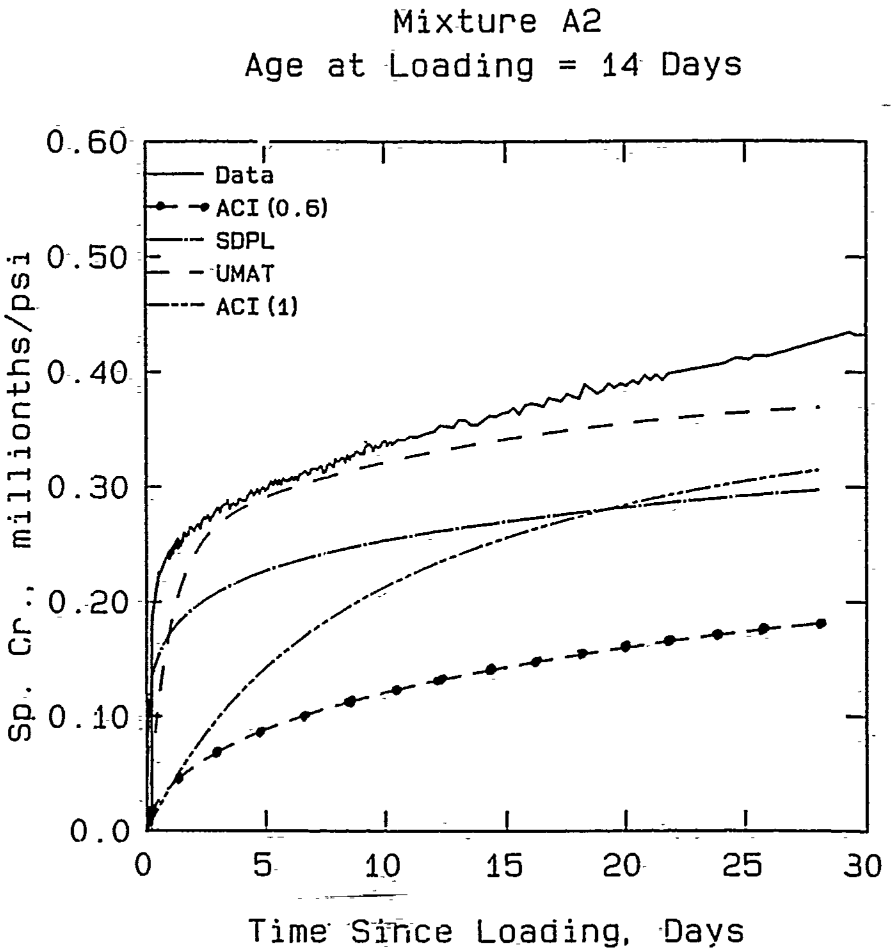

Figure 30. Comparison of test data and creep model predictions from 14-day test on mixture A2

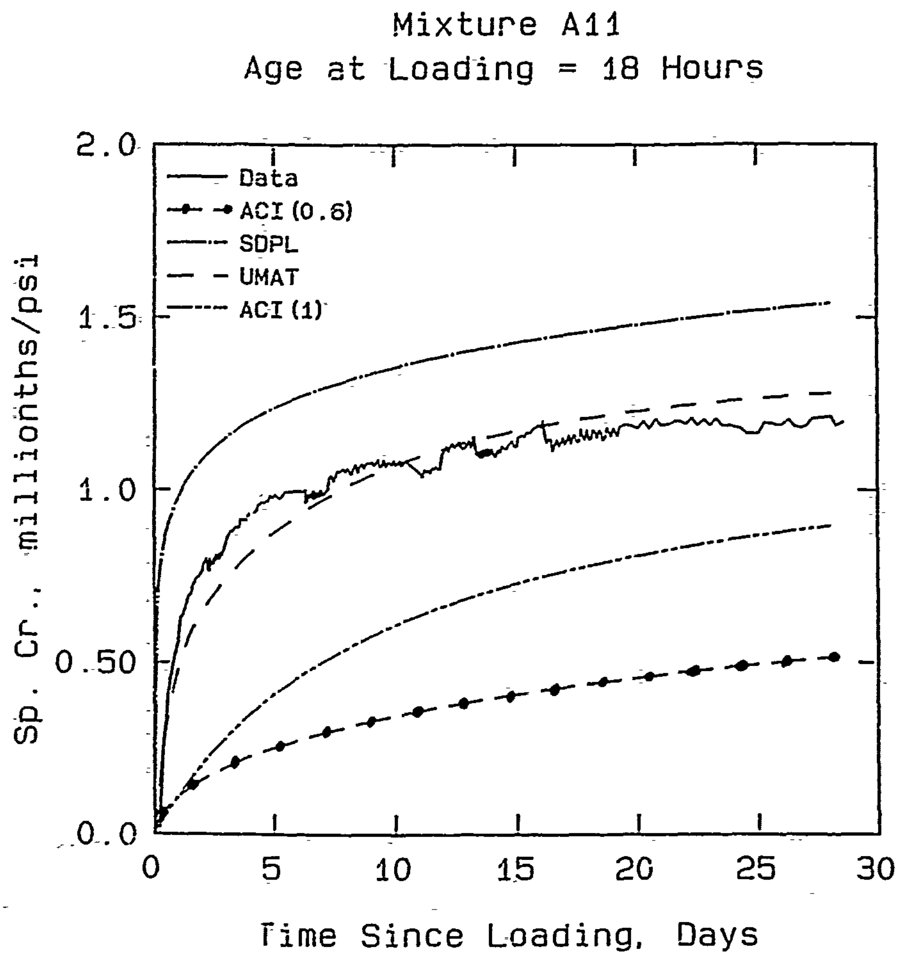

Figure 31. Comparison of test data and creep model predictions from 18-hour test on mixture A11

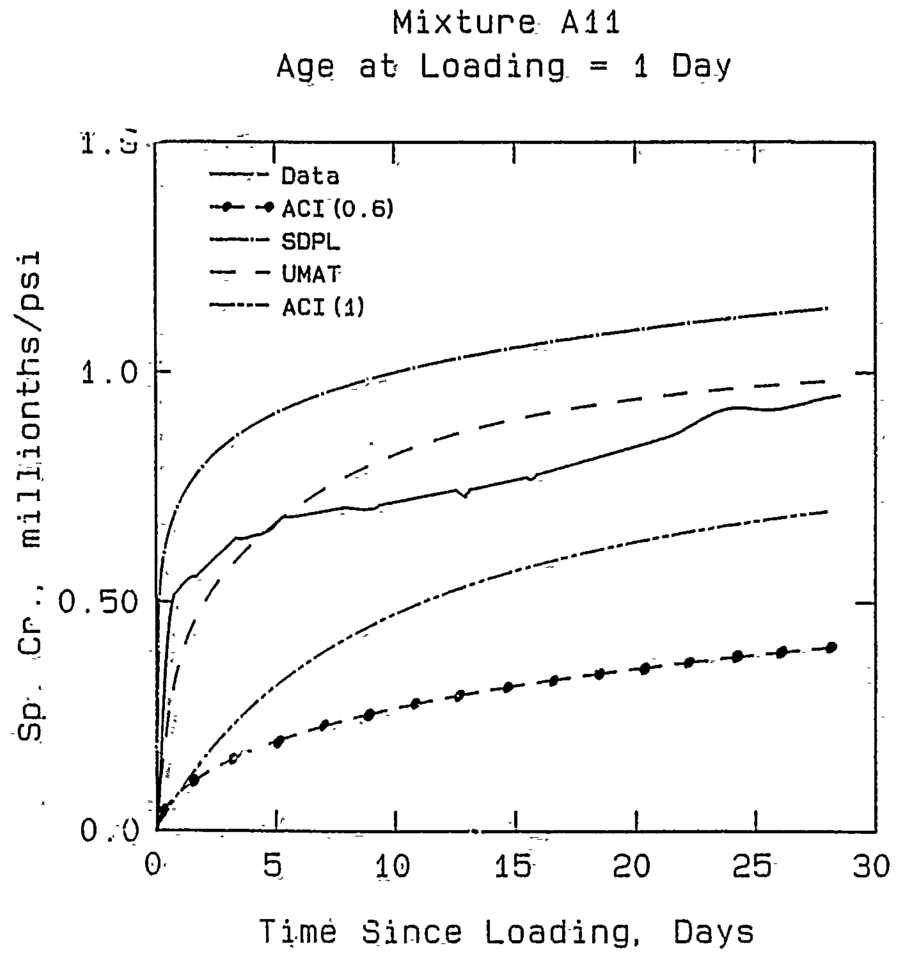

Figure 32. Comparison of test data and creep model predictions from 1-day test on mixture A11

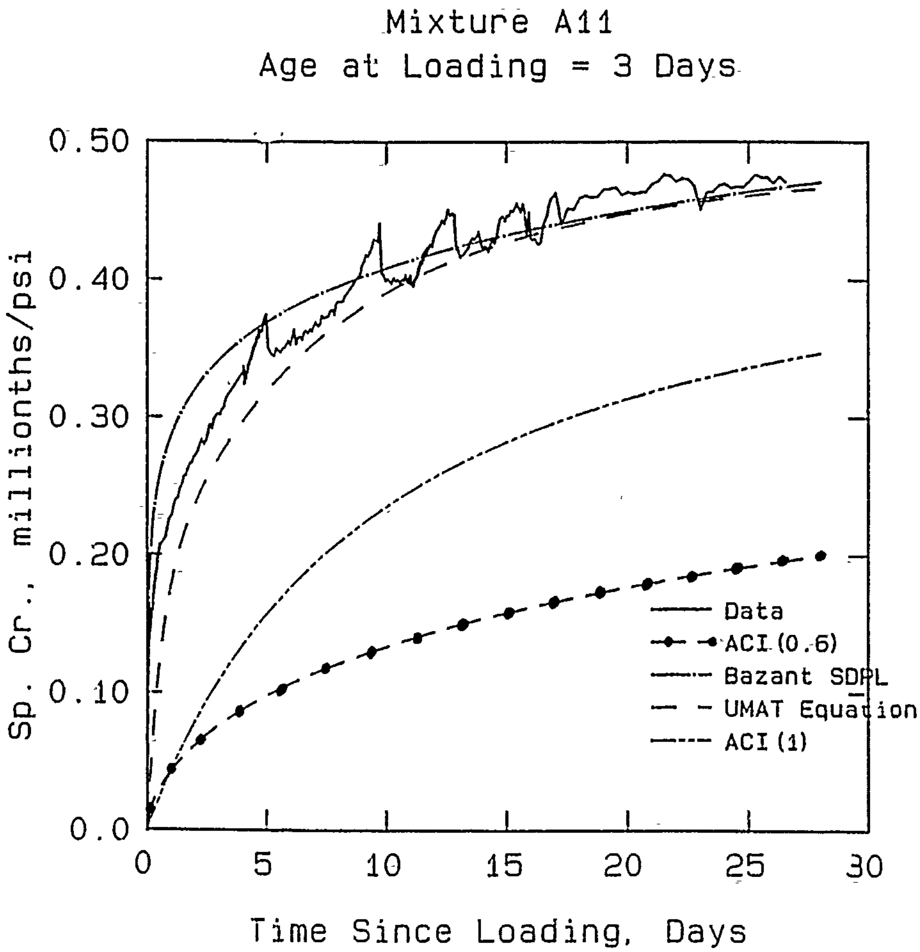

Figure 33. Comparison of test data and creep model predictions from 3-day test on mixture A11

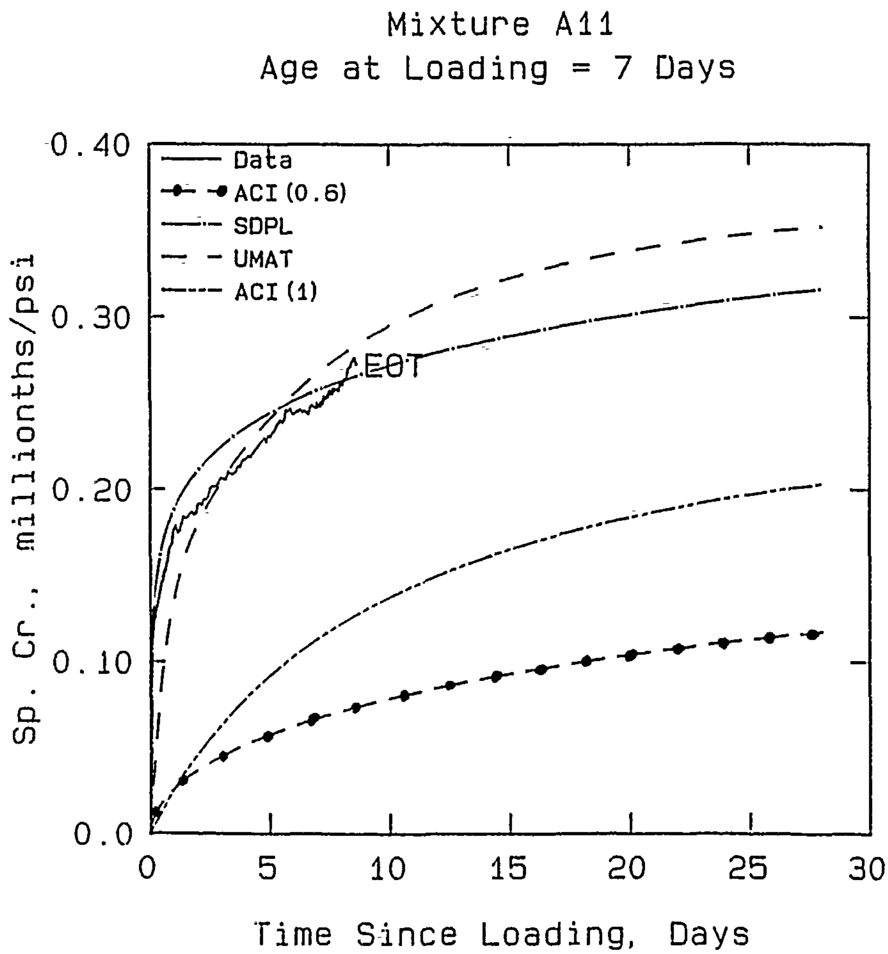

Figure 34. Comparison of test data and creep model predictions from 7-day test on mixture A11

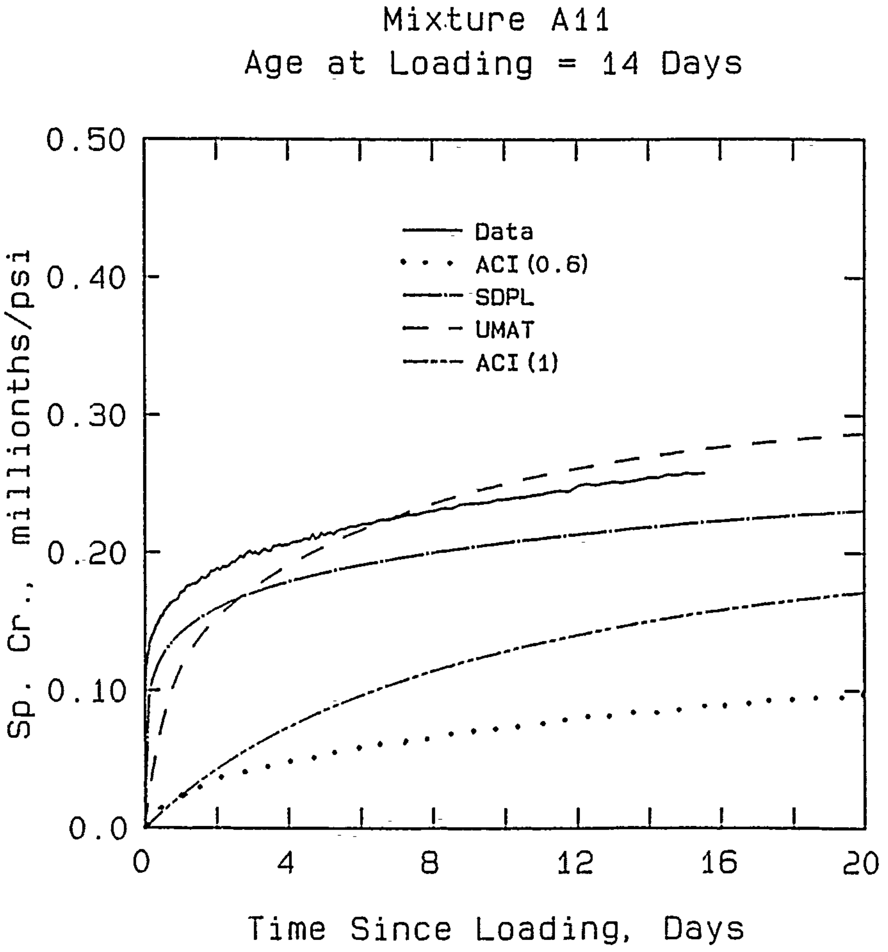

Figure 35. Comparison of test data and creep model predictions from 14-day test on mixture A11

CHAPTER VI: CONCLUSIONS AND RECOMMENDATIONS

62. The rates of increase in compressive strength and modulus of elasticity, especially in the first few days after placement, are critical parameters in predicting construction-related cracking in mass concrete structures. In addition, the removal and anchorage of formwork depend upon the early age strength gain characteristics of the concrete. The rate of development of compressive strength and modulus of elasticity with time is highly dependent on the selection of materials and mixture proportions. Therefore, early age material properties tests should be conducted for each candidate mixture to determine conformity with project requirements. Until more data are obtained, no reliable, universally applicable relationship between early age compressive strength and modulus of elasticity is known to exist. Therefore, early age modulus of elasticity tests should be conducted for any concrete mixture for which it is an important parameter.

63. Since there are major differences in the way that analysts view creep depending on whether one's interest is in reinforced concrete or mass concrete, a general statement about which model is best is not possible. If one's interest is reinforced concrete, a model that closely overpredicts creep response would provide a conservative value when used to determine overall long-term deflections or loss of prestressing force. If one's interest is mass concrete, a model that underpredicts creep would also underpredict the stress-relieving properties of creep and provide a conservative estimate of thermal stress and thermal-related cracking in mass concrete structures.

64. In mass-concrete thermal-stress analysis the early ages (less than 3 days) are more critical than the later ages. In reinforced-concrete analysis, the primary concern is with ages greater than 28 days. The UMAT equation yielded the most conservative and the closest prediction of early time creep response. The UMAT equation may also be expanded with additional terms to refine the response predictions of the model if a particular application required additional accuracy. However, an increase in the number of terms will increase the difficulty encountered in calibration of the model constants. The SDPL equation can be made to closely predict creep response at a given age provided that the equation constants are determined at that particular age of loading. However, the SDPL has demonstrated only a limited ability

to accurately predict creep response at ages of loading other than those used for calibration. The addition of an aging factor similar to the one used in the UMAT equation should be developed for the SDPL in order to make it a more effective analysis tool.

65. Extreme caution should be used when applying conventional concrete material models to mass concrete thermal-stress analysis. The vast differences between structural concrete and typical mass concrete mixtures will usually require that specially developed or modified models be used. It should also be noted that the use of high percentages of pozzolans in mass concrete invalidates most of the suggested values that ACI recommends for use with the ACI creep equations. No universally-applicable, constituent-based model of early-time mass-concrete creep response is known to exist. Therefore, early-time creep tests should be conducted for any concrete mixture for which it is an important parameter. Models such as the SDPL creep equation and the UMAT creep equation will provide rational and consistent results when properly calibrated and verified against accurate test data.

REFERENCES

[1] Norman, C. Dean and Anderson, Fred A. 1985. "Reanalysis of Cracking in Large Concrete Dams in the US Army Corps of Engineers", Proceedings, Fifteenth International Congress On Large Dams, Lausanne, Switzerland.

[2] Norman,C. Dean, Campbell Roy L., and Garner, Sharon B. 1988. "Analysis of Concrete Cracking in Lock Wall Resurfacing", Technical Report REMR-CS-15, US Army Engineer Waterways Experiment Station, Vicksburg, MS 39180.

[3] Neville, A. M. 1981, 1983. Properties of Concrete, Pittman Publishing Inc., Marshfield, MA.

[4] Hammons, M. I., Smith, D. M., and Neeley, Billy D. 1990 (July). "Red River Waterway Thermal Study; Concrete Mixture Selection and Characterization", Report 1, Technical Report SL-90-08, USAE Waterways Experiment Station, Vicksburg, MS 39180.

[5] Garner, S. B., Hammons, M. I., and Bombich, Anthony A. 1991. "Red River Waterway Thermal Study; Thermal Stress Analyses", Report 2, Technical Report SL-90-8, USAE Waterways Experiment Station, Vicksburg, MS 39180.

[6] ACI Committee 318. 1990. "Building Code Requirements for Reinforced Concrete", American Concrete Institute, Detroit, MI.

[7] ACI Committee 209. 1988. "Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures", ACI Manual of Concrete Practice, Part 1, American Concrete Institute, Detroit, MI.

[8] Neville, A. M., Dilger, W. H., and Brooks, J. J. 1983. Creep of Plain and Structural Concrete, Construction Press, New York, NY.

[9] Neville, A. M., and Brooks, J. J. 1987. Concrete Technology, John Wiley and Sons, New York, NY.

[10] Bazant, Z. P., Chern, J. C., and Wu, Y. G. (1989). "Basic Creep Formula for Aging Concrete: Sinh Double Power Law," Cement, Concrete, and Aggregates, Volume 11, Number 2, pp. 85-91.

[11] American Society for Testing and Materials. 1990. 1990 Annual Book of ASTM Standards, Philadelphia, PA.

a. Designation C 39-86. "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens."

b. Designation C 138-81. "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete."

c. Designation C 143-78. "Standard Test Method for Slump of Portland Cement Concrete."

d. Designation C 150-85a. "Standard Specification for Portland Cement."

e. Designation C 191-82. "Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle."

f. Designation C 192-81. "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."

g. Designation C 231-82. "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method."

h. Designation C 311-87. "Standard Test Method for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete."

i. Designation C 403-85. "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance."

j. Designation C 511-85. "Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes."

k. Designation C 512-87. "Standard Test Method for Creep of Concrete in Compression."

l. Designation C 618-85. "Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete."

[12] Raphael, J. M. and Carlson, R. W. 1954. "Measurement of Structural Action in Dams," James J. Gillich & Co., Berkeley, CA

APPENDIX A

CREEP TEST METHOD

Designation: C 512 – 87

Standard Test Method for Creep of Concrete in Compression[1]

This standard is issued under the fixed designation C 512; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of the creep of molded concrete cylinders subjected to sustained longitudinal compressive load. This test method is limited to concrete in which the maximum aggregate size does not exceed 2 in. (50 mm).

1.2 The values stated in inch-pound units are to be regarded as the standard.

1.3 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 39 Test Method for Compressive Strength of Cylindrical Concrete Specimens[2]

C 192 Method of Making and Curing Concrete Test Specimens in the Laboratory[2]

C 470 Specification for Molds for Forming Concrete Test Cylinders Vertically[2]

C 617 Practice for Capping Cylindrical Concrete Specimens[2]

E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

2.2 *American Concrete Institute (ACI):*[3]

Publication SP-9 Symposium on Creep of Concrete

3. Significance and Use

3.1 This test method measures the load-induced time-dependent compressive strain at selected ages for concrete under an arbitrary set of controlled environmental conditions.

3.2 This test method can be used to compare creep potentials of different concretes. A procedure is available, using the developed equation (or graphical plot), for calculating stress from strain data within massive non-reinforced concrete structures. For most specific design applications, the test conditions set forth herein must be modified to more closely simulate the anticipated curing, thermal, exposure, and loading age conditions for the prototype structure. Current theories and effects of material and environmental parameters are presented in ACI SP-9.

3.3 In the absence of a satisfactory hypothesis governing creep phenomena, a number of assumptions have been developed that have been generally substantiated by test and experience.

3.3.1 Creep is proportional to stress from 0 to 40 % of concrete compressive strength.

3.3.2 Creep has been conclusively shown to be directly proportional to paste content throughout the range of paste contents normally used in concrete. Thus the creep characteristics of concrete mixtures containing aggregate of maximum size greater than 2 in. (50 mm) may be determined from the creep characteristics of the minus 2-in. (minus 50-mm) fraction obtained by wet-sieving. Multiply the value of the characteristic by the ratio of the cement paste content (proportion by volume) in the full concrete mixture to the paste content of the sieved sample.

3.4 The use of the logarithmic expression (Section 8) does not imply that the creep strain-time relationship is necessarily an exact logarithmic function; however, for the period of one year, the expression approximates normal creep behavior with sufficient accuracy to make possible the calculation of parameters that are useful for the purpose of comparing concretes.

3.5 There are no data that would support the extrapolation of the results of this test to tension or torsion.

4. Apparatus

4.1 *Molds*—Molds shall be cylindrical conforming to the general provisions of 2.1 of Method C 192 and to the specific provisions of 2.2.1 or 2.2.3 of Method C 192, whichever is applicable; or to the provisions of Specification C 470. If required, provisions shall be made for attaching gage studs and inserts, and for affixing integral bearing plates to the ends of the specimen as it is cast.

4.1.1 Horizontal molds shall conform to the general requirements of 2.1 of Method C 192 and to the specific provisions of 2.2.3 thereof. A horizontal mold that has proven satisfactory is shown in Fig. 1.

4.2 *Loading Frame*, capable of applying and maintaining the required load on the specimen, despite any change in the dimension of the specimen. In its simplest form the loading frame consists of header plates bearing on the ends of the loaded specimens, a load-maintaining element that may be either a spring or a hydraulic capsule or ram, and threaded rods to take the reaction of the loaded system. Bearing surfaces of the header plates shall not depart from a plane by more than 0.001 in. (0.025 mm). In any loading frame, several specimens may be stacked for simultaneous loading.

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[1] This test method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.02.03 on Elastic and Inelastic Properties of Concrete.

Current edition approved July 9, 1987. Published August 1987. Originally published as C 512 – 63 T. Last previous edition C 512 – 82 (1983)$^{\epsilon 1}$.

[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] Available from the American Concrete Institute, P. O. Box 19150, Detroit, MI 48219.

FIG. 1 Horizontal Mold for Creep Specimens

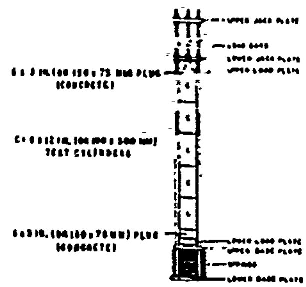


FIG. 2 Spring-Loaded Creep Frame

The length between header plates shall not exceed 70 in. (1780 mm). When a hydraulic load-maintaining element is used, several frames may be loaded simultaneously through a central hydraulic pressure-regulating unit consisting of an accumulator, a regulator, indicating gages, and a source of high pressure, such as a cylinder of nitrogen or a high-pressure pump. Springs such as railroad car springs may be used to maintain the load in frames similar to those described above; the initial compression shall be applied by means of a portable jack or testing machine. When springs are used, care should be taken to provide a spherical head or ball joint, and end plates rigid enough to ensure uniform loading of the cylinders. Figure 2 shows an acceptable spring-loaded frame. Means shall be provided for measuring the load to the nearest 2 % of total applied load. This may be a permanently installed hydraulic pressure gage or a hydraulic jack and a load cell inserted in the frame when the load is applied or adjusted.

4.3 *Strain-Measuring Device*—Suitable apparatus shall be provided for the measurement of longitudinal strain in the specimen to the nearest 10 millionths. The apparatus may be embedded, attached, or portable. If a portable apparatus is used, gage points shall be attached to the specimen in a positive manner. Attached gages relying on friction contact are not permissible. If an embedded device is used, it shall be situated so that its strain movement occurs along the longitudinal axis of the cylinder. If external devices are used, strains shall be measured on not less than two gage lines spaced uniformly around the periphery of the specimen. The gages may be instrumented so that the average strain on all gage lines can be read directly. The effective gage length shall be at least three times the maximum size of aggregate in the concrete. The strain-measuring device shall be capable of measuring strains for at least 1 year without change in calibration.

NOTE 1—Systems in which the varying strains are compared with a constant-length standard bar are considered most reliable, but unbonded electrical strain gages are satisfactory.

5. Test Specimens

5.1 *Specimen Size*—The diameter of each specimen shall be 6 ± 1/16 in. (or 150 ± 1.6 mm), and the length shall be at least 11½ in. (292 mm). When the ends of the specimen are in contact with steel bearing plates, the specimen length shall be at least equal to the gage length of the strain-measuring apparatus plus the diameter of the specimen. When the ends of the specimen are in contact with other concrete specimens similar to the test specimen, the specimen length shall be at least equal to the gage length of the strain-measuring apparatus plus 1½ in. (38 mm). Between the test specimen and the steel bearing plate at each end of a stack, a supplementary noninstrumented cylinder whose diameter is equal to that of the test cylinders and whose length is at least half its diameter shall be installed.

5.2 *Fabricating Specimens*—The maximum size of aggregate shall not exceed 2 in. (50-mm) (Section 3). Vertically cast cylinders shall be fabricated in accordance with the provisions of Section 5 of Method C 192. The ends of each cylinder shall meet the planeness requirements of 1.2 of Practice C 617 (Note 2). Horizontally cast specimens shall be consolidated by the method appropriate to the consistency of the concrete as indicated in 5.4.1 of Method C 192. Care must be taken to ensure that the rod or vibrator does not strike the strain meter. When vibration is used, the concrete shall be placed in one layer and the vibrating element shall not exceed 1¼ in. (32 mm) in diameter. When rodding is used, the concrete shall be placed in two approximately equal layers and each layer shall be rodded 25 times evenly along each side of the strain meter. After consolidation the concrete shall be struck off with trowel or float, then trowelled the minimum amount to form the concrete in the opening concentrically with the rest of the specimen. A template curved in the radius of the specimen may be used as a strikeoff to shape and finish the concrete more precisely in the opening. When cylinders are to be stacked, lapping of ends is strongly recommended.

NOTE 2—Requirements for planeness may be met by capping, lapping, or, at the time of casting, fitting the ends with bearing plates normal to the axis of the cylinder.

5.3 *Number of Specimens*—No fewer than six specimens (Note 3) shall be made from a given batch of concrete for each test condition: two shall be tested for compressive strength, two shall be loaded and observed for total deformation, and two shall remain unloaded for use as controls to indicate deformations due to causes other than load. Each strength and control specimen shall undergo the same curing and storage treatment as the loaded specimen.

NOTE 3—It is recommended that specimens be tested in triplicate although duplicate specimens are acceptable.

6. Curing and Storage of Specimens

6.1 *Standard Curing*—Before removal from the molds, specimens shall be stored at 73.4 ± 3.0°F (23.0 ± 1.7°C) and covered to prevent evaporation. The specimens shall be removed from the molds not less than 20 nor more than 48 h after molding and stored in a moist condition at a temperature of 73.4 ± 3.0°F until the age of 7 days. A moist condition is that in which free water is maintained on the surfaces of the specimens at all times. Specimens shall not be exposed to a stream of running water nor be stored in water. After the completion of moist curing the specimens shall be stored at a temperature of 73.4 ± 2.0°F (23.0 ± 1.1°C) and at a relative humidity of 50 ± 4 % until completion of the test.

6.2 *Basic Creep Curing*—If it is desired to prevent the gain or loss of water during the storage and test period, specimens shall at the time of fabrication or stripping be enclosed and sealed in moistureproof jackets (for example, copper or butyl rubber) to prevent loss of moisture by evaporation and shall remain sealed throughout the period of storage and testing.

6.3 *Variable Curing Temperature Regimen*—When it is desired to introduce the effect of temperature on the elastic and inelastic properties of a concrete (as, for example, the adiabatic temperature conditions existing in massive concrete or temperature conditions to which concrete is subjected during accelerated curing), temperatures within the specimen storage facility shall be controlled to correspond to the desired temperature history. The user shall be responsible for establishing the time-temperature history to be followed and the permissible range of deviation therefrom.

6.4 *Other Curing Conditions*—Other test ages and ambient storage conditions may be substituted when information is required for specific applications. The storage conditions shall be carefully detailed in the report.

7. Procedure

7.1 *Age at Loading*—When the purpose of the test is to compare the creep potential of different concretes, initially load the specimens at an age of 28 days. When the complete creep behavior of a given concrete is desired, prepare the specimens for initial loading in the following ages: 2, 7, 28, and 90 days, and 1 year. If information is desired for other ages of loading, include the age in the report.

7.2 *Loading Details*—Immediately before loading the creep specimens, determine the compressive strength of the strength specimens in accordance with Test Method C 39. At the time unsealed creep specimens are placed in the loading frame, cover the ends of the control cylinders to prevent loss of moisture (Note 4). Load the specimens at an intensity of not more than 40 % of the compressive strength at the age of loading. Take strain readings immediately before and after loading, 2 to 6 h later, then daily for 1 week, weekly until the end of 1 month, and monthly until the end of 1 year. Before taking each strain reading, measure the load. If the load varies more than 2 % from the correct value, it must be adjusted (Note 5). Take strain readings on the control specimens on the same schedule as the loaded specimens.

NOTE 4—In placing creep specimens in the frame, take care in aligning the specimens to avoid eccentric loading. When cylinders are stacked and external gages are used, it may be helpful to apply a small preload such that the resultant stress does not exceed 200 psi (1380 kPa) and note the strain variation around each specimen, after which the load may be removed and the specimens realigned for greater strain uniformity.

NOTE 5—Where springs are used to maintain the load, the adjustment can be accomplished by applying the correct load and tightening the nuts on the threaded reaction rods.

8. Calculation

8.1 Calculate the total load-induced strain per pound per square inch (or kilopascal) at any time as the difference between the average strain values of the loaded and control specimens divided by the average stress. To determine creep strain per pound-force per square inch (or kilopascal) for any age, subtract from the total load-induced strain per pound-force per square inch (or kilopascal) at that age the strain per pound-force per square inch (or kilopascal) immediately after loading. If desired, plot total strain per pound-force per square inch (or kilopascal) on semilog coordinate paper, on which the logarithmic axis represents time, to determine the constants $1/E$ and $F(K)$ for the following equation:

$$\epsilon = (1/E) + F(K)\ln(t + 1)$$

where:

ϵ = total strain psi (or kPa),
E = instantaneous elastic modulus, psi (or kPa),
$F(K)$ = creep rate, calculated as the slope of a straight line representing the creep curve on the semilog plot, and
t = time after loading, days.

The quantity $1/E$ is the initial elastic strain per pound per square inch (or kilopascal) and is determined from the strain readings taken immediately before and after loading the specimen. If loading was not accomplished expeditiously, some creep may have occurred before the after-loading strain was observed, in which event extrapolation to zero time by the method of least squares may be used to determine this quantity.

9. Report

9.1 The report shall include the following:

9.1.1 Cement content, water-cement ratio, maximum aggregate size, slump, and air content.

9.1.2 Type and source of cement, aggregate, admixture, and mixing water (if other than fresh water is used).

9.1.3 Position of cylinder when cast.

9.1.4 Storage conditions prior to and subsequent to loading.

9.1.5 Age at time of loading.

9.1.6 Compressive strength at age of loading.

9.1.7 Type of strain measuring device.

9.1.8 Magnitude of any preload.

(Issued 1 Jun. 1989)

4 Standard Test Method for Creep of Concrete in Compression (C 512-87) (C 54-89)

9.1.9 Intensity of applied load.

9.1.10 Initial elastic strain.

9.1.11 Creep strain per pound per square inch (or kilopascal) at designated ages up to 1 year, and

9.1.12 Creep rate, $F(K)$, if determined.

10. Precision and Bias

10.1 *Precision*—The single-operator-batch precision has been found to be ±4.0 % (R1S %), and the single-operator-multi-batch precision has been found to be ±9.0 % (R1S %), as defined in Practice E 177, over the range of creep strains from 250 to 2000 millionths; therefore, the results of properly conducted tests of duplicate cylinders from a single batch should agree within 6 % of the average of the two, and the results of properly conducted tests of duplicate cylinders from different batches should agree within 13 % of the average of the two.

10.2 *Bias*—This test method has no bias because the values determined can only be defined in terms of the test method.

APPENDIX B

COMPRE   STRENGTH TEST METHOD

Designation: C 39 – 86[ε1]

American Association State Highway and Transportation Officials Standard
AASHTO No. T 22

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race St., Philadelphia, Pa. 19103

Standard Test Method for COMPRESSIVE STRENGTH OF CYLINDRICAL CONCRETE SPECIMENS[1]

This standard is issued under the fixed designation C 39; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This method has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards

[ε1] NOTE—Editorial changes were made throughout in June 1986.

1. Scope

1.1 This test method covers determination of compressive strength of cylindrical concrete specimens such as molded cylinders and drilled cores. It is limited to concrete having a unit weight in excess of 50 lb/ft^3 (800 kg/m^3).

1.2 The values stated in inch-pound units are to be regarded as the standard.

1.3 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Applicable Documents

2.1 *ASTM Standards:*

C 31 Method of Making and Curing Concrete Test Specimens in the Field[2]

C 42 Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete[2]

C 192 Method of Making and Curing Concrete Test Specimens in the Laboratory[2]

C 617 Practice for Capping Cylindrical Concrete Specimens[2]

C 873 Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds[2]

E 4 Practices for Load Verification of Testing Machines[2]

E 74 Practice for Calibration of Force-Measuring Instruments for Verifying the Load Indication of Testing Machines[3]

2.2 *Other:*

Manual of Aggregate and Concrete Testing

3. Summary of Method

3.1 This test method consists of applying a compressive axial load to molded cylinders or cores at a rate which is within a prescribed range until failure occurs. The compressive strength of the specimen is calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen.

4. Significance and Use

4.1 Care must be exercised in the interpretation of the significance of compressive strength determinations by this test method since strength is not a fundamental or intrinsic property of concrete made from given materials. Values obtained will depend on the size and shape of the specimen, batching, mixing procedures, the methods of sampling, molding, and fabrication and the age, temperature, and moisture conditions during curing.

4.2 This test method may be used to deter-

[1] This test method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.03.01 on Methods of Testing Concrete for Strength.

Current edition approved March 27, 1986. Published May 1986. Originally published as C 39 – 21 T. Last previous edition C 39 – 84.

[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 03.01

mine compressive strength of cylindrical specimens prepared and cured in accordance with Methods C 31, C 42, and C 192, Practice C 617, and Test Method C 873.

4.3 The results of this test method may be used as a basis for quality control of concrete proportioning, mixing, and placing operations; determination of compliance with specifications; control for evaluating effectiveness of admixtures and similar uses.

5. Apparatus

5.1 *Testing Machine*—The testing machine shall be of a type having sufficient capacity and capable of providing the rates of loading prescribed in 7.5.

5.1.1 Verification of calibration of the testing machines in accordance with Practices E 4 is required under the following conditions:

5.1.1.1 After an elapsed interval since the previous verification of 18 months maximum, but preferably after an interval of 12 months,

5.1.1.2 On original installation or relocation of the machine,

5.1.1.3 Immediately after making repairs or adjustments which may in any way affect the operation of the weighing system or the values displayed, except for zero adjustments that compensate for the weight of tooling, or specimen, or both, or

5.1.1.4 Whenever there is reason to doubt the accuracy of the results, without regard to the time interval since the last verification.

5.1.2 *Design*—The design of the machine must include the following features:

5.1.2.1 The machine must be power operated and must apply the load continuously rather than intermittently, and without shock. If it has only one loading rate (meeting the requirements of 7.5), it must be provided with a supplemental means for loading at a rate suitable for verification. This supplemental means of loading may be power or hand operated.

5.1.2.2 The space provided for test specimens shall be large enough to accommodate, in a readable position, an elastic calibration device which is of sufficient capacity to cover the potential loading range of the testing machine and which complies with the requirements of Practices E 74.

NOTE 1—The type of elastic calibration device most generally available and most commonly used for this purpose is the circular proving ring.

5.1.3 *Accuracy*—The accuracy of the testing machine shall be in accordance with the following provisions:

5.1.3.1 The percentage of error for the loads within the proposed range of use of the testing machine shall not exceed ±1.0 % of the indicated load.

5.1.3.2 The accuracy of the testing machine shall be verified by applying five test loads in four approximately equal increments in ascending order. The difference between any two successive test loads shall not exceed one third of the difference between the maximum and minimum test loads.

5.1.3.3 The test load as indicated by the testing machine and the applied load computed from the readings of the verification device shall be recorded at each test point. Calculate the error, E, and the percentage of error, E_p, for each point from these data as follows:

$$E = A - B$$
$$E_p = 100(A - B)/B$$

where:

A = load, lbf (or N) indicated by the machine being verified, and

B = applied load, lbf (or N) as determined by the calibrating device.

5.1.3.4 The report on the verification of a testing machine shall state within what loading range it was found to conform to specification requirements rather than reporting a blanket acceptance or rejection. In no case shall the loading range be stated as including loads below the value which is 100 times the smallest change of load that can be estimated on the load-indicating mechanism of the testing machine or loads within that portion of the range below 10 % of the maximum range capacity.

5.1.3.5 In no case shall the loading range be stated as including loads outside the range of loads applied during the verification test.

5.1.3.6 The indicated load of a testing machine shall not be corrected either by calculation or by the use of a calibration diagram to obtain values within the required permissible variation.

5.2 The testing machine shall be equipped with two steel bearing blocks with hardened faces (Note 2), one of which is a spherically seated block that will bear on the upper surface of the specimen, and the other a solid block on which the specimen shall rest. Bearing faces of the blocks shall have a minimum dimension at least 3 % greater than the diameter of the specimen to be tested. Except for the concentric circles described below, the bearing faces shall not depart from a plane by more than 0.001 in. (0.025 mm) in any 6 in. (152 mm) of blocks 6 in. in diameter or larger, or by more than 0.001 in. in the diameter of any smaller block; and new blocks shall be manufactured within one half of this tolerance. When the diameter of the bearing face of the spherically seated block exceeds the diameter of the specimen by more than ½ in. (13 mm), concentric circles not more than 1/32 in. (0.8 mm) deep and not more than 3/64 in. (1.2 mm) wide shall be inscribed to facilitate proper centering.

NOTE 2—It is desirable that the bearing faces of blocks used for compression testing of concrete have a Rockwell hardness of not less than 55 HRC.

5.2.1 Bottom bearing blocks shall conform to the following requirements:

5.2.1.1 The bottom bearing block is specified for the purpose of providing a readily machinable surface for maintenance of the specified surface conditions (Note 3). The top and bottom surfaces shall be parallel to each other. The block may be fastened to the platen of the testing machine. Its least horizontal dimension shall be at least 3 % greater than the diameter of the specimen to be tested. Concentric circles as described in 5.2 are optional on the bottom block.

5.2.1.2 Final centering must be made with reference to the upper spherical block. When the lower bearing block is used to assist in centering the specimen, the center of the concentric rings, when provided, or the center of the block itself must be directly below the center of the spherical head. Provision shall be made on the platen of the machine to assure such a position.

5.2.1.3 The bottom bearing block shall be at least 1 in. (25 mm) thick when new, and at least 0.9 in. (22.5 mm) thick after any resurfacing operations.

NOTE 3—If the testing machine is so designed that the platen itself can be readily maintained in the specified surface condition, a bottom block is not required.

5.2.2 The spherically seated bearing block shall conform to the following requirements:

5.2.2.1 The maximum diameter of the bearing face of the suspended spherically seated block shall not exceed the values given below:

Diameter of Test Specimens, in. (mm)	Maximum Diameter of Bearing Face, in. (mm)
2(51)	4(102)
3(76)	5(127)
4(102)	6½(165)
6(152)	10(254)
8(203)	11(279)

NOTE 4—Square bearing faces are permissible, provided the diameter of the largest possible inscribed circle does not exceed the above diameter.

5.2.2.2 The center of the sphere shall coincide with the surface of the bearing face within a tolerance of ±5 % of the radius of the sphere. The diameter of the sphere shall be at least 75 % of the diameter of the specimen to be tested.

5.2.2.3 The ball and the socket must be so designed by the manufacturer that the steel in the contact area does not permanently deform under repeated use, with loads up to 12 000 psi (82.7 MPa) on the test specimen.

NOTE 5—The preferred contact area is in the form of a ring (described as preferred "bearing" area) as shown on Fig. 1.

5.2.2.4 The curved surfaces of the socket and of the spherical portion shall be kept clean and shall be lubricated with a petroleum-type oil such as conventional motor oil, not with a pressure type grease. After contacting the specimen and application of small initial load, further tilting of the spherically seated block is not intended and is undesirable.

5.2.2.5 If the radius of the sphere is smaller than the radius of the largest specimen to be tested, the portion of the bearing face extending beyond the sphere shall have a thickness not less than the difference between the radius of the sphere and radius of the specimen. The least dimension of the bearing face shall be at least as great as the diameter of the sphere (see Fig. 1).

5.2.2.6 The movable portion of the bearing block shall be held closely in the spherical seat, but the design shall be such that the bearing face can be rotated freely and tilted at least 4° in any direction.

5.3 *Load Indication:*

5.3.1 If the load of a compression machine used in concrete testing is registered on a dial, the dial shall be provided with a graduated scale that can be read to at least the nearest 0.1 % of the full scale load (Note 6). The dial shall be readable within 1 % of the indicated load at any given load level within the loading range. In no case shall the loading range of a dial be considered to include loads below the value that is 100 times the smallest change of load that can be read on the scale. The scale shall be provided with a graduation line equal to zero and so numbered. The dial pointer shall be of sufficient length to reach the graduation marks; the width of the end of the pointer shall not exceed the clear distance between the smallest graduations. Each dial shall be equipped with a zero adjustment that is easily accessible from the outside of the dial case, and with a suitable device that at all times until reset, will indicate to within 1 % accuracy the maximum load applied to the specimen.

NOTE 6—As close as can reasonably be read is considered to be 1/50 in. (0.5 mm) along the arc described by the end of the pointer. Also, one half of a scale interval is about as close as can reasonably be read when the spacing on the load indicating mechanism is between 1/25 in. (1 mm) and 1/16 in. (1.6 mm). When the spacing is between 1/16 in. and 1/8 in. (3.2 mm), one third of a scale interval can be read with reasonable certainty. When the spacing is 1/8 in. or more, one fourth of a scale interval can be read with reasonable certainty.

5.3.2 If the testing machine load is indicated in digital form, the numerical display must be large enough to be easily read. The numerical increment must be equal to or less than 0.10 % of the full scale load of a given loading range. In no case shall the verified loading range include loads less than the minimum numerical increment multiplied by 100. The accuracy of the indicated load must be within 1.0 % for any value displayed within the verified loading range. Provision must be made for adjusting to indicate true zero at zero load. There shall be provided a maximum load indicator that at all times until reset will indicate within 1 % system accuracy the maximum load applied to the specimen.

6. Specimens

6.1 Specimens shall not be tested if any individual diameter of a cylinder differs from any other diameter of the same cylinder by more than 2 %.

NOTE 7—This may occur when single use molds are damaged or deformed during shipment, when flexible single use molds are deformed during molding or when a core drill deflects or shifts during drilling.

6.2 Neither end of compressive test specimens when tested shall depart from perpendicularity to the axis by more than 0.5° (approximately equivalent to 1/8 in. in 12 in. (3 mm in 300 mm)). The ends of compression test specimens that are not plane within 0.002 in. (0.050 mm) shall be capped in accordance with Practice C 617 or they may be sawed or ground to meet that tolerance. The diameter used for calculating the cross-sectional area of the test specimen shall be determined to the nearest 0.01 in. (0.25 mm) by averaging two diameters measured at right angles to each other at about midheight of the specimen.

6.3 The number of individual cylinders measured for determination of average diameter may be reduced to one for each ten specimens or three specimens per day, whichever is greater, if all cylinders are known to have been made from a single lot of reusable or single-use molds which consistently produce specimens with average diameters within a range of 0.02 in. (0.51 mm). When the average diameters do not fall within the range of 0.02 in. or when the cylinders are not made from a single lot of molds, each cylinder tested must be measured and the value used in calculation of the unit compressive strength of that specimen. When the diameters are measured at the reduced frequency, the cross-sectional areas of all cylinders tested on that day shall be computed from the average of the diameters of the three or more cylinders representing the group tested that day.

6.4 The length shall be measured to the nearest 0.05 D when the length to diameter ratio is less than 1.8, or more than 2.2, or when the volume of the cylinder is determined from measured dimensions.

7. Procedure

7.1 Compression tests of moist-cured specimens shall be made as soon as practicable after removal from moist storage.

7.2 Test specimens shall be kept moist by any convenient method during the period between removal from moist storage and testing. They shall be tested in the moist condition.

7.3 All test specimens for a given test age shall be broken within the permissible time tolerances prescribed as follows:

Test Age	Permissible Tolerance
24 h	±0.5 h or 2.1 %
3 days	2 h or 2.8 %
7 days	6 h or 3.6 %
28 days	20 h or 3.0 %
90 days	2 days 2.2 %

7.4 *Placing the Specimen*—Place the plain (lower) bearing block, with its hardened face up, on the table or platen of the testing machine directly under the spherically seated (upper) bearing block. Wipe clean the bearing faces of the upper and lower bearing blocks and of the test specimen and place the test specimen on the lower bearing block. Carefully align the axis of the specimen with the center of thrust of the spherically seated block. As the spherically seated block is brought to bear on the specimen, rotate its movable portion gently by hand so that uniform seating is obtained.

7.5 *Rate of Loading*—Apply the load continuously and without shock.

7.5.1 For testing machines of the screw type, the moving head shall travel at a rate of approximately 0.05 in. (1.3 mm)/min when the machine is running idle. For hydraulically operated machines, the load shall be applied at a rate of movement (platen to crosshead measurement) corresponding to a loading rate on the specimen within the range of 20 to 50 psi/s (0.14 to 0.34 MPa/s). The designated rate of movement shall be maintained at least during the latter half of the anticipated loading phase of the testing cycle.

7.5.2 During the application of the first half of the anticipated loading phase a higher rate of loading shall be permitted.

7.5.3 Make no adjustment in the rate of movement of the platen at any time while a specimen is yielding rapidly immediately before failure.

7.6 Apply the load until the specimen fails, and record the maximum load carried by the specimen during the test. Note the type of failure and the appearance of the concrete.

8. Calculation

8.1 Calculate the compressive strength of the specimen by dividing the maximum load carried by the specimen during the test by the average cross-sectional area determined as described in Section 6 and express the result to the nearest 10 psi (69 kPa).

8.2 If the specimen length to diameter ratio is less than 1.8, correct the result obtained in 8.1 by multiplying by the appropriate correction factor shown in the following table:

L/D:	1.75	1.50	1.25	1.00
Factor:	0.98	0.96	0.93	0.87 (Note 8)

NOTE 8—These correction factors apply to lightweight concrete weighing between 100 and 120 lb/ft^3 (1600 and 1920 kg/m^3) and to normal weight concrete. They are applicable to concrete dry or soaked at the time of loading. Values not given in the table shall be determined by interpolation. The correction factors are applicable for nominal concrete strengths from 2000 to 6000 psi (13.8 to 41.4 MPa).

9. Report

9.1 The report shall include the following:

9.1.1 Identification number,

9.1.2 Diameter (and length, if outside the range of 1.8*D* to 2.2*D*), in inches or millimetres,

9.1.3 Cross-sectional area, in square inches or square centimetres,

9.1.4 Maximum load, in pounds-force or newtons,

9.1.5 Compressive strength calculated to the nearest 10 psi or 69 kPa,

9.1.6 Type of fracture, if other than the usual cone (see Fig. 2),

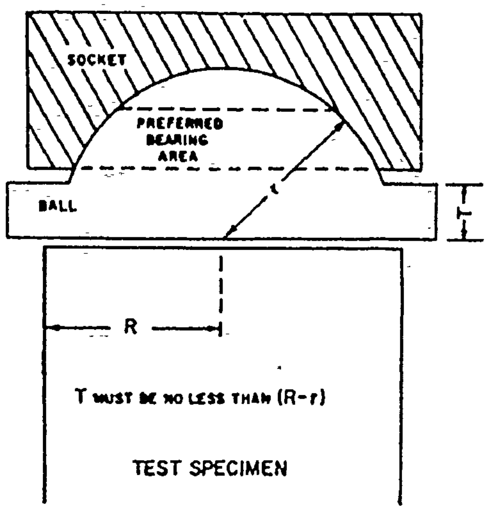
9.1.7 Defects in either specimen or caps, and,

9.1.8 Age of specimen.

10. Precision

10.1 The precision of this test method has not yet been determined, but data are being collected, and a precision statement will be included when it is formulated.[4]

[4] See "Concrete Strength in Structures," by D. L. Bloem, *ACI Journal*, March 1968, especially Table 3, p. 185, for possible guidance as to the level of reproducibility of concrete strength measurements that may be expected.



NOTE—Provision shall be made for holding the ball in the socket and for holding the entire unit in the testing machine.

FIG. 1 Schematic Sketch of a Typical Spherical Bearing Block

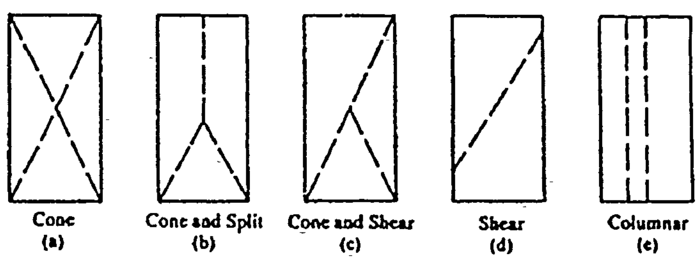


FIG. 2 Sketches of Types of Fracture

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APPENDIX C

CARLSON STRAIN GAGES

Physical Construction

1. The Carlson strain meter (or gage) is in the general form of a long cylinder with anchors on the end to engage the surrounding concrete. Within the flexible brass cover tube, a steel framework supports porcelain spools around which are wound, under 100,000-psi tension, two equal coils of 0.0025-in. diameter steel music wire. A schematic drawing of a Carlson strain meter is shown in Figure 36.

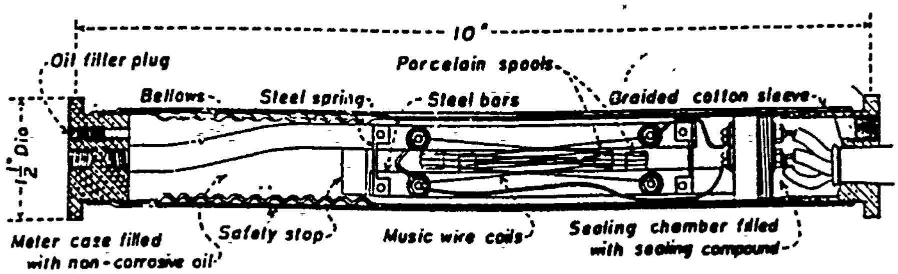

Figure 36. Carlson strain meter

Principle of Operation

2. The instrument is designed to take advantage of two electrical properties of steel wire: resistance of the wire varies directly with temperature and with the tension on the wire. When the ends of the strain meter are pulled apart by an expansion in concrete, the outer or expansion coil elongates and increases in tension and, consequently, in resistance as well. At the same time, the inner or contraction coil decreases in resistance as it shortens. The ratio of the resistance of the expansion coil to the resistance of the contraction coil, which at all times is very near unity, is used as a sensitive measure of length change in the strain meter. A typical meter

usually calibrates to about 4 millionths of an inch per inch per 0.01 percent change in ratio. Resistance ratio changes are not affected by simultaneous temperature changes of the wire since the temperature change affects both coils by an equal percentage.

3. Temperature is measured by taking the sum of the resistance of the expansion and contraction coils. This sum is not affected materially by variation in resistance due to length changes, as these plus and minus values very nearly cancel each other in the sum. The resistance of the miniature meter is about 60 ohms at 72°F, and increases about 1 ohm for every 9°F rise in temperature. A correction of 6.7 millionths of an inch per inch for each 1°F change of temperature must be made for the expansion of the strain meter frame. Actual calibration data are provided for each instrument.

Measurement Technique--Wheatstone Bridge

4. Strains are determined in the Carlson strain meter by a measurement of the resistance change in the expansion and contraction coils. There is a direct relation between the resistance change and the strain of the coils of the meter. This strain is measured with a data acquisition unit that employs the Wheatstone bridge technique in a balanced configuration as shown in Figure 37. Two of the four arms required to make up the bridge circuit are in the meter itself. The other two arms are in the data acquisition unit.

5. Each coil in a new meter will be approximately equal in resistance. It can be assumed without error that each arm is equal in resistance and that any subsequent strain after placement in concrete will cause the expansion arm to increase by the amount of ΔR and simultaneously produce a decrease of ΔR in the contraction arm. Later calculations will show the miniature meter to have a gage factor of about 6. This means that the percentage change in resistance ($\Delta R/R \times 100$) is six times the percentage change in the length of the meter (AL/L x 100). In contrast, a bonded SR-4 strain gage has a factor of about 2.

Factory Calibration Constants

6. Two calibration constants are given on the factory calibration sheet. One is the relationship of strain to the least reading and the other

the relationship of the resistance change with temperature. Typical calibration constants for the SM-4 meter are 8.18 microstrains/least reading and 12.27°F/ohm. Also, the resistance of the meter is given on the calibration sheet for a temperature of 0°F. It is then possible to calculate the temperature for any known resistance or vice versa [12].

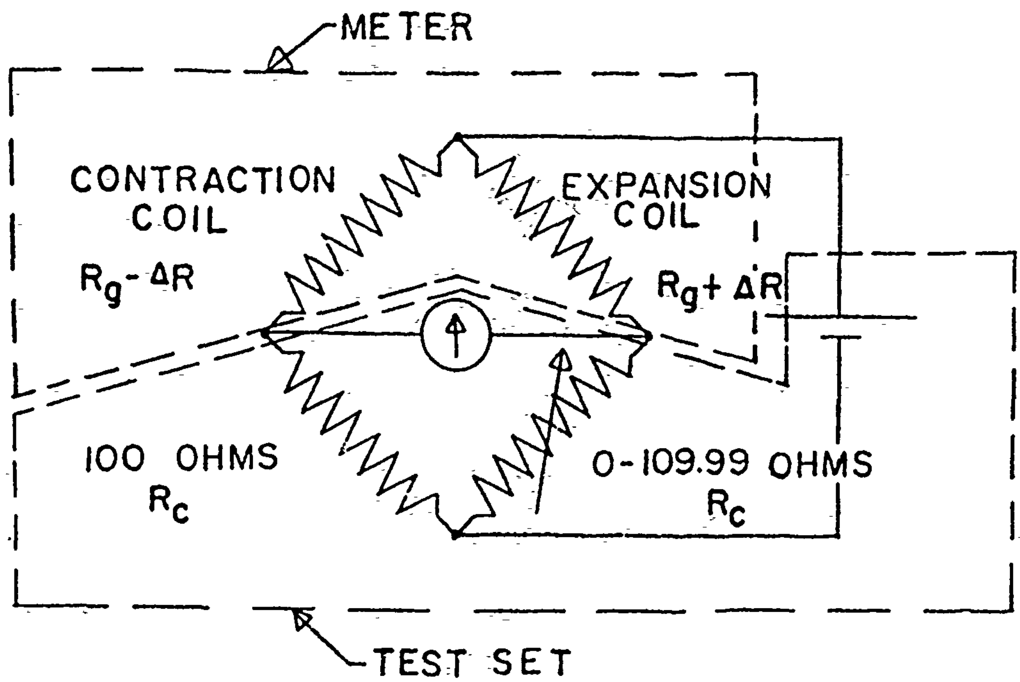

Figure 37. Electrical schematic of Carlson meter setup

APPENDIX D

CREEP TEST DATA

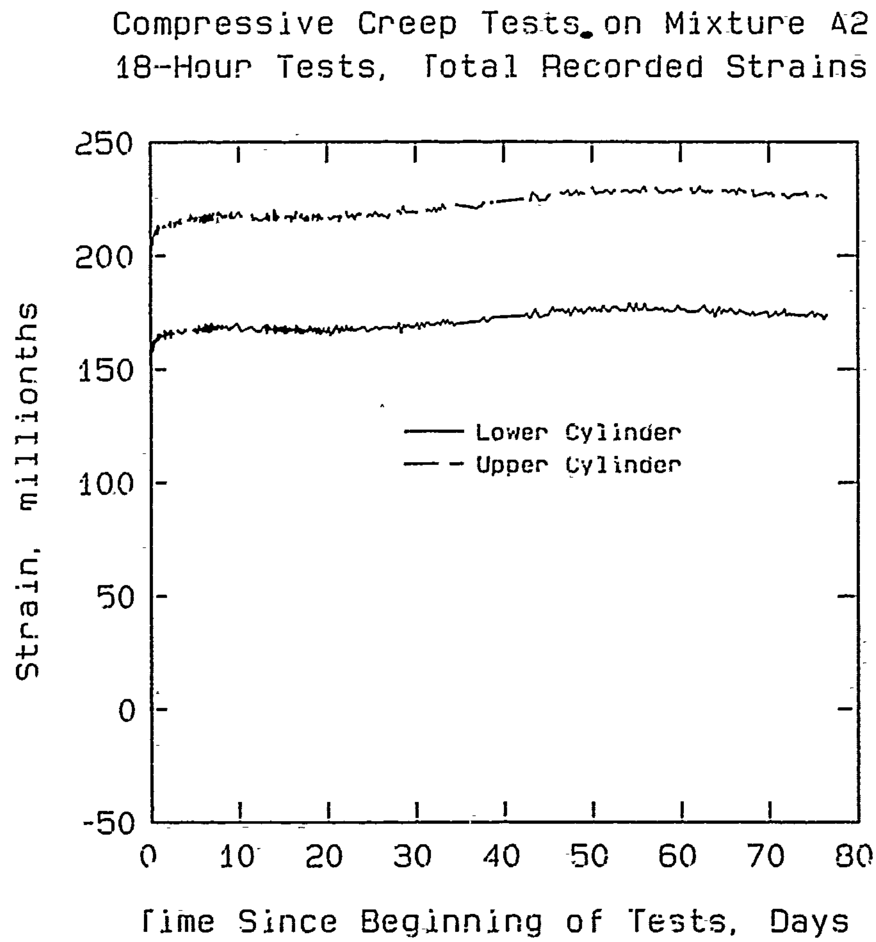

Figure 38. Creep test data from 18-hour test on mixture A2

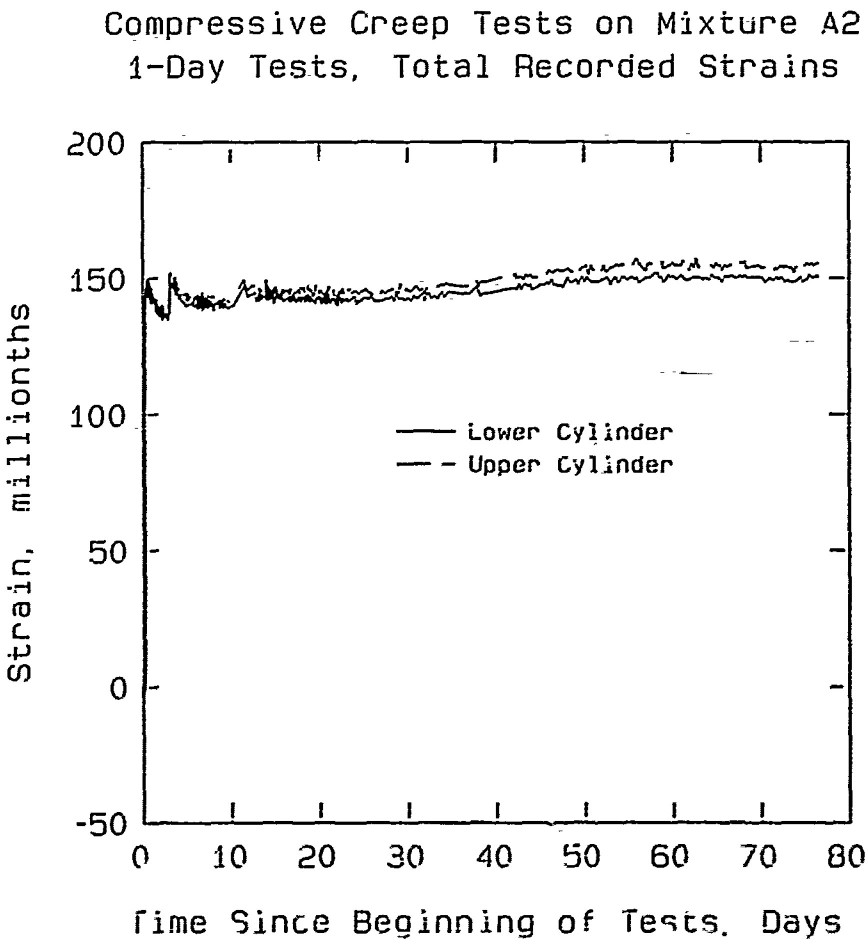

Figure 39. Creep test data from 1-day test on mixture A2

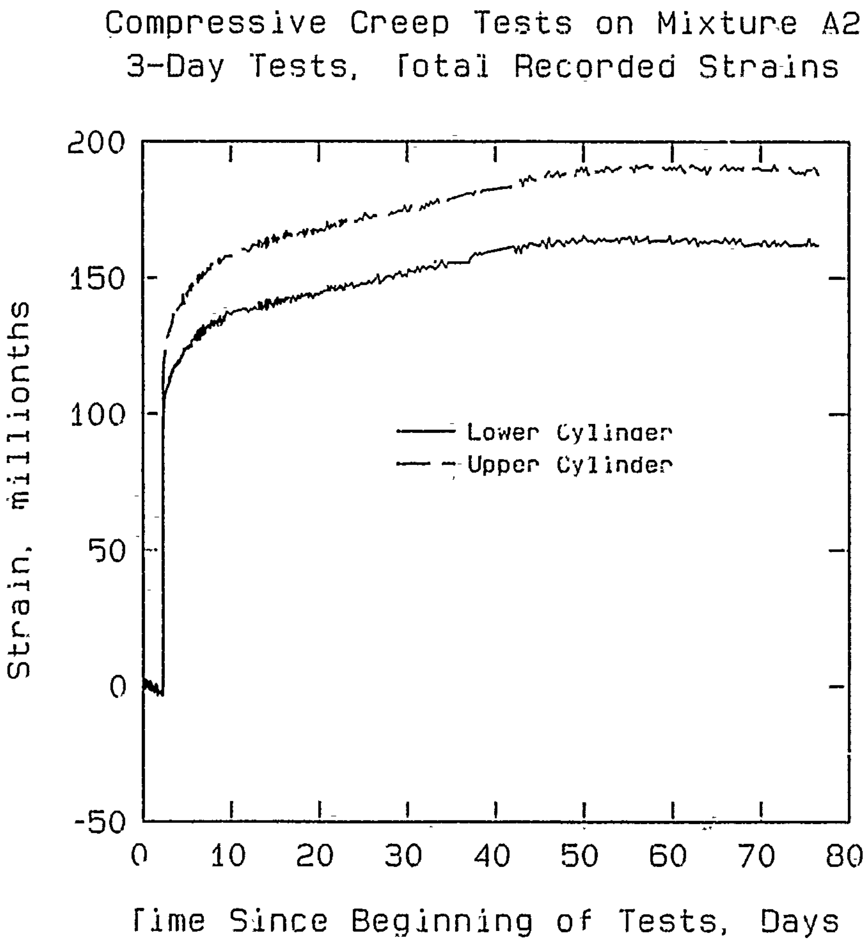

Figure 40. Creep test data from 3-day test on mixture A2

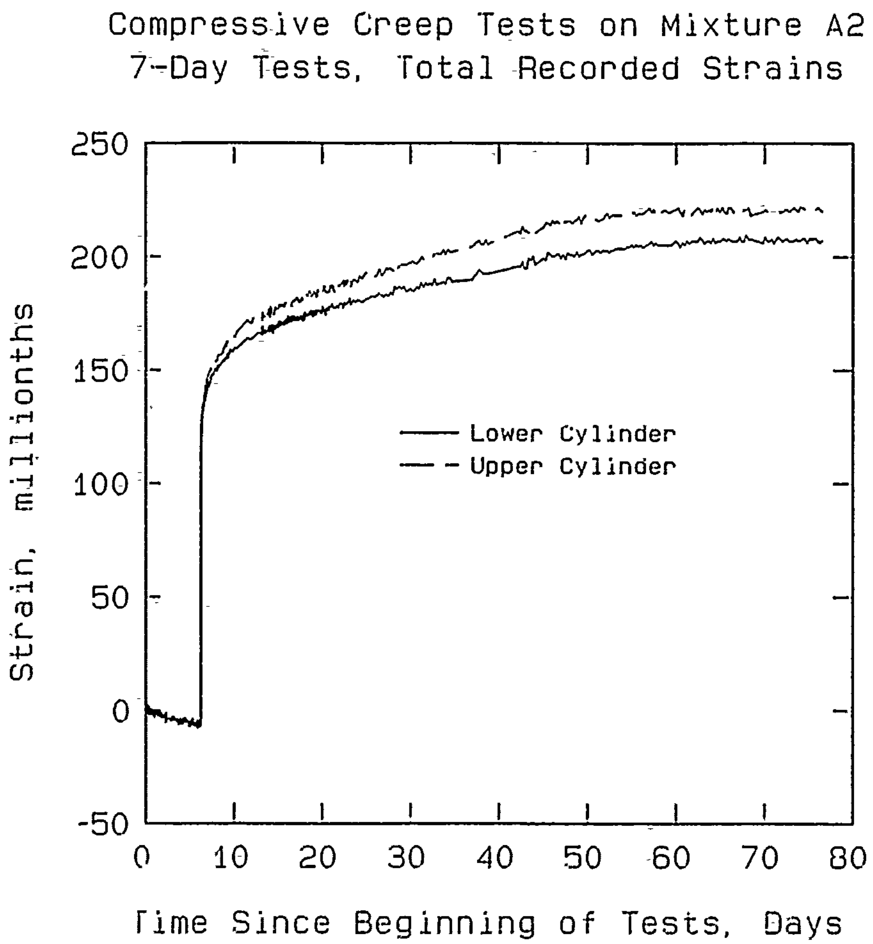

Figure 41. Creep test data from 7-day test on mixture A2

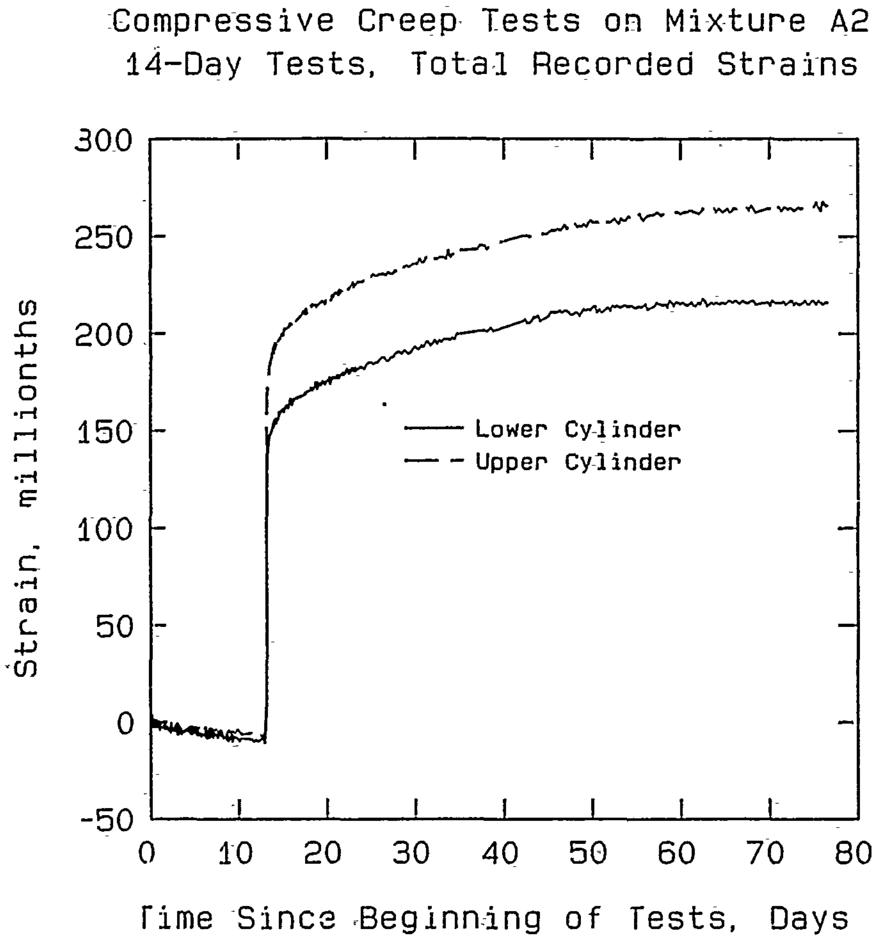

Figure 42. Creep test data from 14-day test on mixture A2

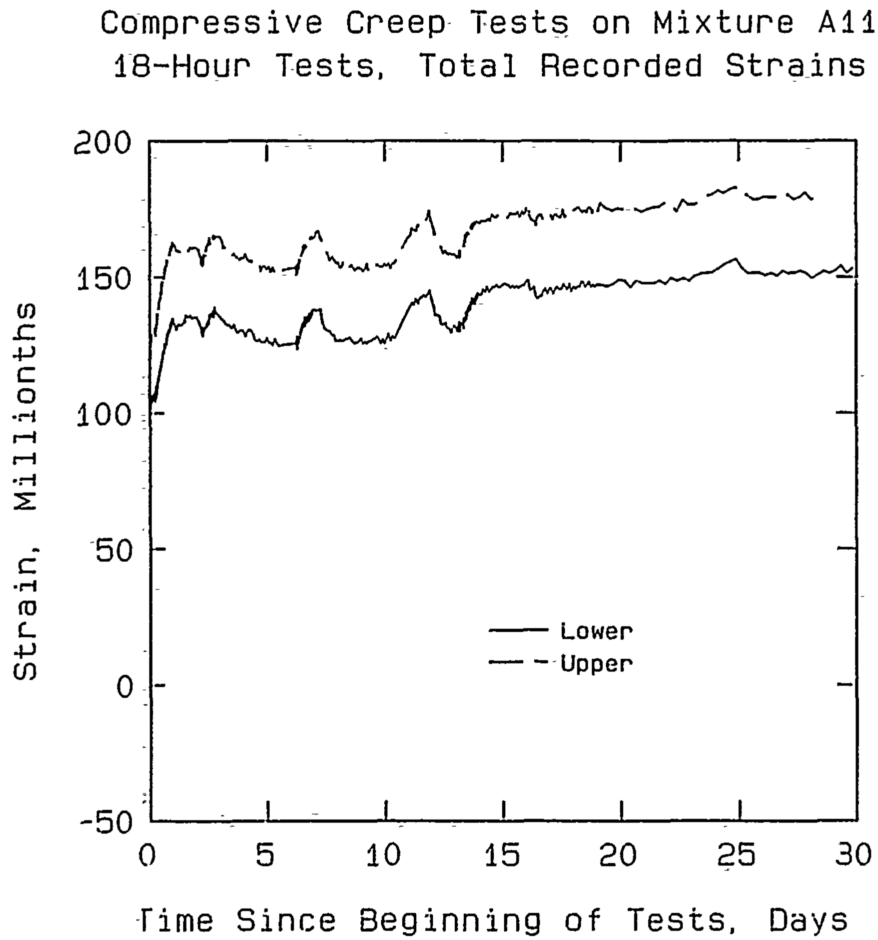

Figure 43. Creep test data from 18-hour test on mixture A11

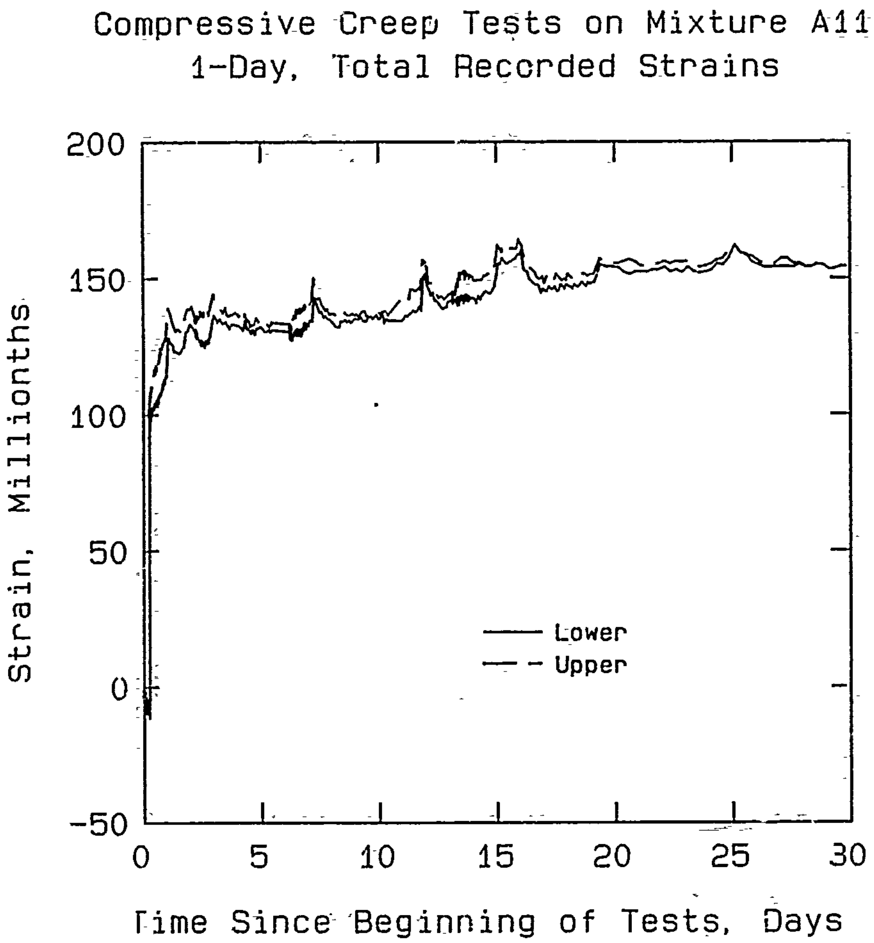

Figure 44. Creep test data from 1-day test on mixture All

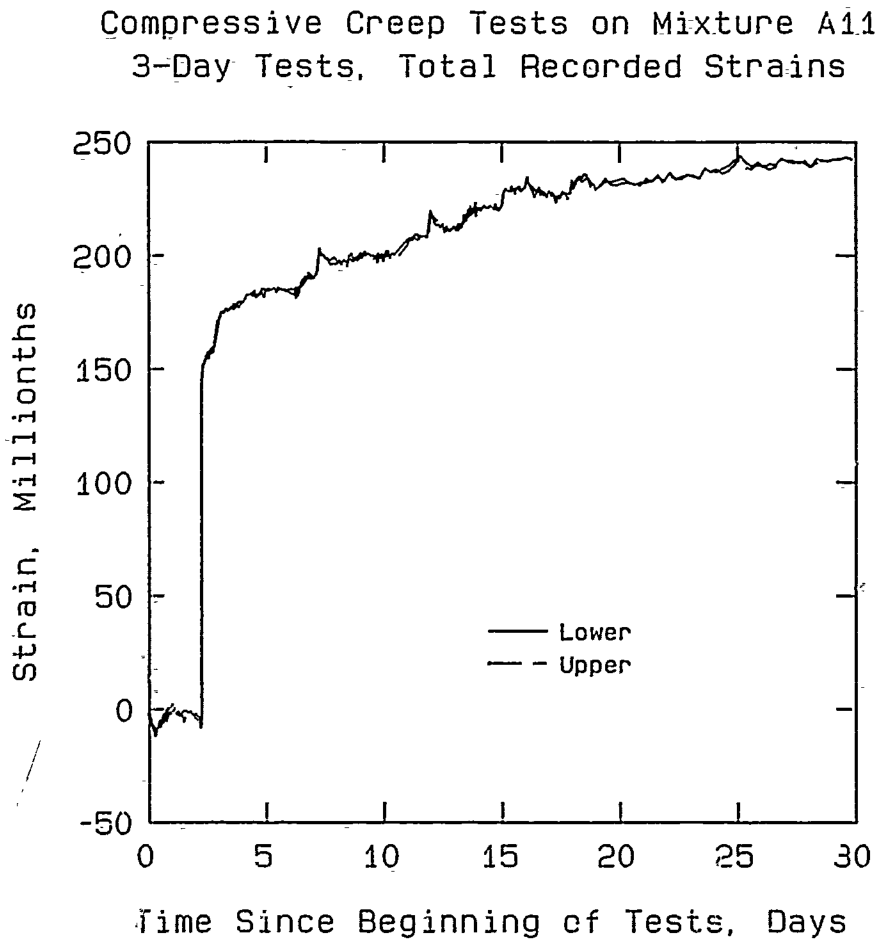

Figure 45. Creep test data from 3-day test on mixture A11

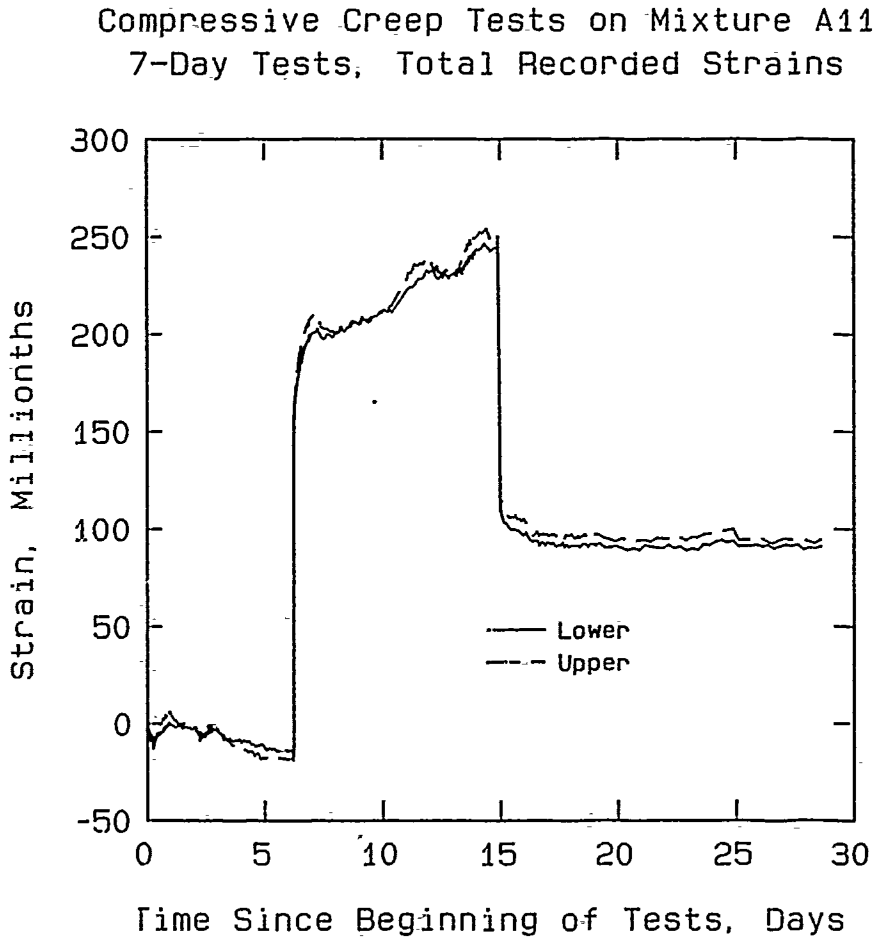

Figure 46. Creep test data from 7-day test on mixture A11

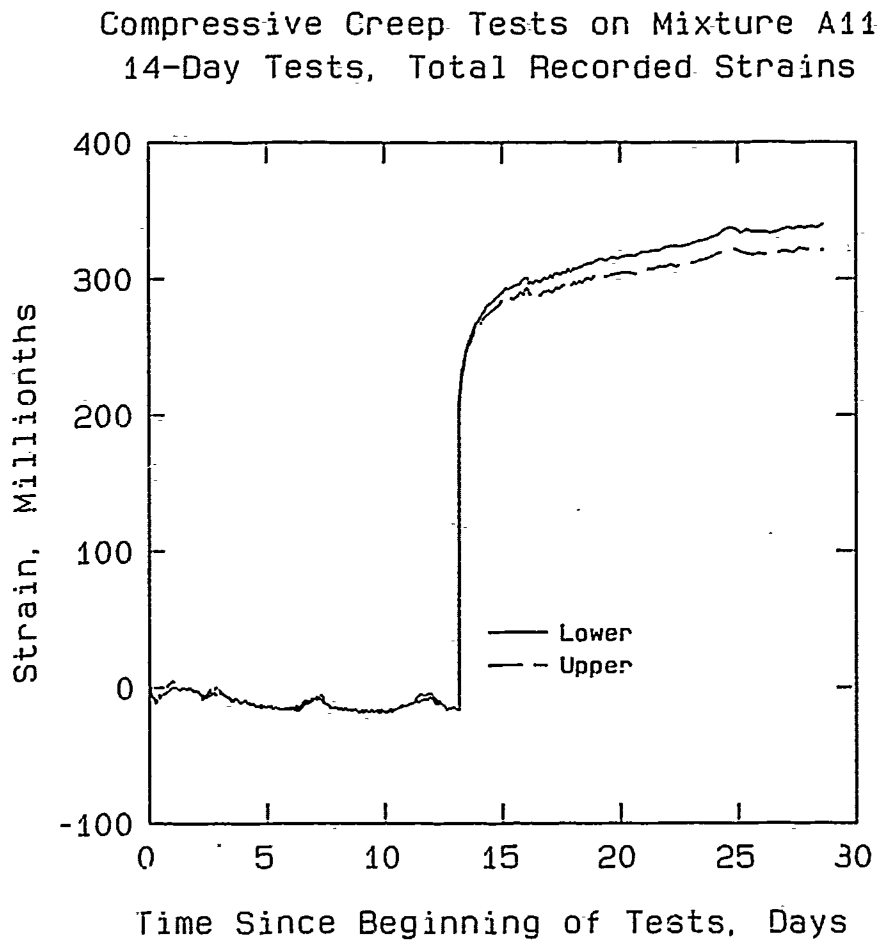

Figure 47. Creep test data from 14-day test on mixture All

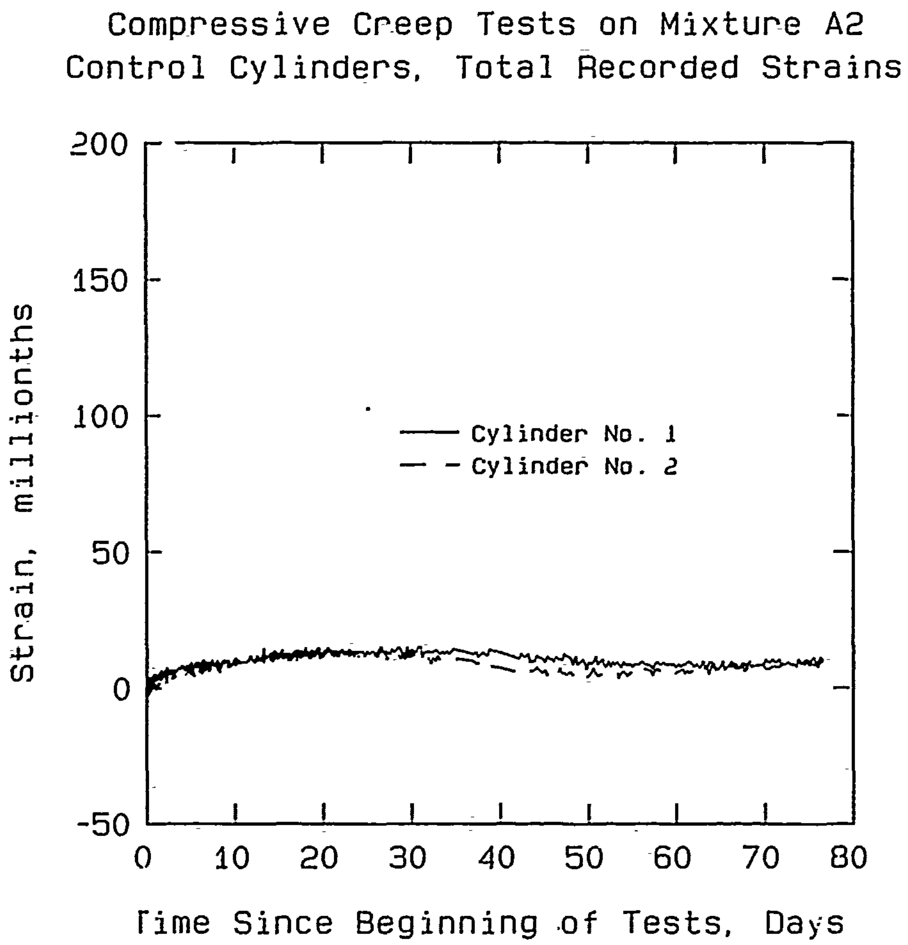

Figure 48. Control cylinders for mixture A2

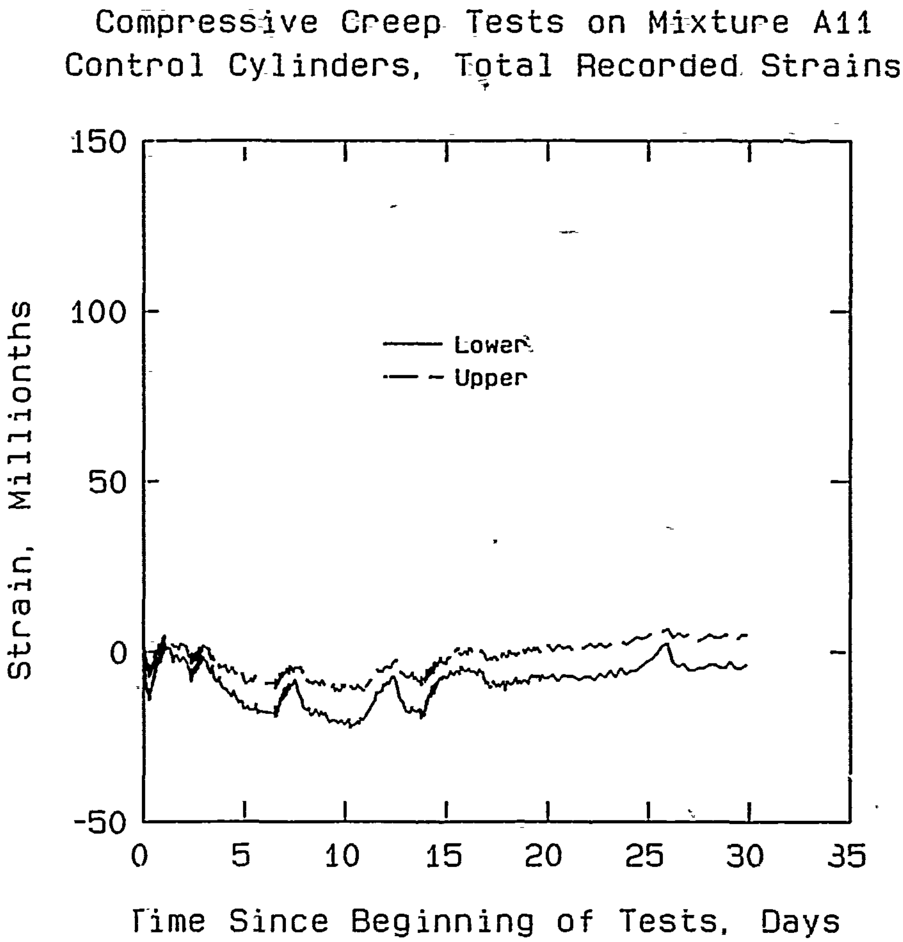

Figure 49. Control cylinders for mixture All